RESEARCH & DEVELOPMENT

Compatibility Testing of Supplemental Fall Protection Devices on NCDOT Bridges

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16. Abstract

Falls from bridge decks is a common safety issue among bridge maintenance and inspection workers. These workers traditionally rely on existing bridge guardrails for their protection against falls when performing on-the-deck work operations. However, a disproportionate number of the bridge guardrails do not provide sufficient protection based on the 42 ± 3 in. regulatory barrier height requirement. One proactive and effective intervention that the North Carolina Department of Transportation (NCDOT) and a few other transportation agencies have adopted is the installation of Fall Protection Supplementary Devices (FPSDs) – to temporarily increase the barrier height during work. However, many manufactured and marketed FPSDs are not compatible – or do not firmly attach onto every bridge guardrail. Therefore, workers are often tasked with assessing the compatibility of FPSDs with particular bridge guardrails before initiating work. Traditionally, this has been performed using an inefficient trial-and-error based approach – where potential FPSDs are procured, transported, and iteratively tested with a number of bridge guardrails. Apart from this inefficient testing procedure, current literature does not offer any guidance on the selection of efficient FPSDs based on the advantages they offer. Consequently, compatible FPSDs that are not optimal for safety, productivity, and work-efficiency are regularly adopted in practice. To address this issue, the reported research focused on identifying compatible FPSDs – that offer the most advantages – for over 22,000 bridge guardrails across the state of North Carolina. The study objectives were accomplished by (1) building virtual prototypes of existing bridge guardrails and FPSD systems and assessing compatibility in a virtual setting; (2) identifying desirable FPSD characteristics that can lead to improvements in work-efficiency, productivity, and safety; (3) evaluating potential FPSD systems for each guardrail using the structured Choosing by Advantages (CBA) method; and (4) conducting field experiments with workers where physiological responses and productivity rates were monitored. The finding suggests that the adoption of the CC120 offers the most benefits in terms of safety, productivity, and work-efficiency. The findings of this research addresses a significant and nationwide safety and work-efficiency issue experienced by all transportation agencies as reported by AASHTO (American Association of State Highway and Transportation Officials)

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EXECUTIVE SUMMARY

Apart from struck-by safety incidents, fall-related injuries are a major concern in bridge maintenance and inspection work. To prevent falls during on-the-deck operations, bridge maintenance and inspection workers commonly rely on existing bridge guardrails as a safety barrier. However, a large number of bridge guardrails do not comply with the regulatory height requirement of 42 ± 3 in. for sufficient fall protection – although appropriate for vehicular traffic. Therefore workers relying on these bridge guardrails are susceptible to experiencing falls while working on bridge decks.

To address this fall protection issue, a few transportation agencies including the North Carolina Department of Transportation (NCDOT) have proactively adopted Fall Protection Supplementary Devices (FPSDs) to protect their workforce. These devices are temporarily installed on existing bridge guardrails to sufficiently increase the barrier height while work is performed on bridge decks. Unfortunately, not all FPSDs that are manufactured and marketed are compatible with every bridge guardrail. Therefore, to provide sufficient protection, DOT decision makers are tasked with identifying FPSDs that are compatible for each guardrail application. This has traditionally been performed using an inefficient trial-and-error based approach – where potential FPSDs are procured, transported, and iteratively tested with a number of bridge guardrails. The use these inefficient techniques have resulted in significant errors, wasted resources, productivity losses, and an increased likelihood of struck-by safety incidents.

To overcome this issue, the objective of the study was to identify compatible FPSDs – that offer the most advantages – for over 22,000 bridge guardrails across the state of North Carolina. The study objectives were completed in a number of sequential phases.

In the first phase, the most common bridge guardrails that do not offer sufficient protection across the state of North Carolina were identified. Likewise, a market study was conducted to identify and catalogue a comprehensive list of FPSD systems that were to be tested. Using this database, virtual models of the bridge guardrails and the FPSDs were developed and the compatibility was tested safety and efficiently in a virtual setting.

Given that FPSDs compatible with more than 22,000 bridge guardrails were identified, the second phase focused on further evaluating the FPSDs to identify those that offered the most advantages in terms of safety, productivity, and work efficiency. This was accomplished by first identifying the desirable characteristics of FPSDs systems through a collaborative effort with NCDOT managers, supervisors, and workers and applying the systematic Choosing by Advantages (CBA) decision-making approach. The results of this phase identified the FPSD systems that offered the most advantages as follows: (1) Fall Protection Guardrail Systems LLC – CC-120, (2) Fall Protection Guardrail Systems LLC – MCC-130, and (3) Ellis Manufacturing – GRS-P12.

The final phase focused on field evaluations where four candidate FPSDs were tested to assess utility, usability, and the associated safety implications captured using wearable devices. As part of this effort, six experiments were conducted with bridge maintenance workers where they performed routine tasks including loading, unloading, installing, and dismantling of the tested FPSDs. During the experiment, the workers physiological responses, productivity rates, and their perception on utility and usability was gathered. Overall, the study findings suggest the Fall Protection Guardrail Systems LLC – CC-120 is the preferable choice to sufficiently protect workers while also improving work-efficiency and productivity. The approach described in the study and the findings efficiently addresses a nationwide safety and work-efficiency issue experienced by all transportation agencies in the United States.

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INTRODUCTION

Workers involved in the construction and maintenance of transportation infrastructure such as highways and bridges are highly susceptible to occupational injuries. Estimates reveal that over 20,000 transportation workers are injured every year during work (Federal Highway Administration, 2015). Apart from struck-by safety incidents (~ 35%), transportation workers suffer a disproportionate number of fall-related injuries (~ 20%) (Lincoln and Fosbroke, 2010). This is especially true among bridge maintenance workers who spend extensive time working at heights. For example, more than 80% of fall-related fatal incidents occur when work is performed on bridge decks (Pegula 2013). Apart from the emotional and physical distress, these injuries result in substantial injury cost and economic loss (Zou and Sunindijo, 2015).

To prevent fall injuries while working on decks, bridge workers have traditionally relied on existing bridge guardrails as a safety barrier. However, a large number of bridge guardrails in the United States – designed based on the American Association of State Highway and Transportation Officials (AASHTO) standards – do not provide sufficient protection as required by the Occupational Safety and Health Administration (OSHA). In fact, more than 72% (i.e., 83 out of 115) of the bridge guardrails approved for use in the National Highway System fall below the regulatory minimum requirement of 39 inches (Federal Highway Administration, 2014). To address this issue, some departments of transportation (DOTs) have begun to install Fall Protection Supplementary Devices (FPSDs) to temporarily increase the height while work is performed on bridge decks.

However, a significant challenge experienced by DOTs is that a large number of manufactured FPSD systems are not compatible – or do not firmly attach to all bridge guardrails. Therefore, DOTs are often tasked with evaluating the compatibility of individual FPSDs with specific bridge guardrails prior to initiating work. This has traditionally been achieved by procuring potential FPSD systems and physically testing its compatibility with specific guardrails.

Unfortunately, the manual trial-and-error based approach is extremely tedious, ineffective, and uneconomical. For example, the process requires the transportation and installation of FPSD systems to assess compatibility prior to initiating work. In many cases, when the FPSD system is found to be incompatible, alternate compatible products may not immediately be available to initiate work. More importantly, the traditional compatibility testing approach unduly exposes workers to increased risk of falls (i.e., guardrails that do not provide sufficient fall protection) and struck-by safety incidents from vehicular traffic for extended periods.

Because of such challenges, several DOTs have been discouraged from adopting FPSDs as a prospective solution for fall protection in favor of less effective alternatives. To assess the extent of this issue, we developed a questionnaire survey that was administered to the North American Association of Transportation Safety and Health Officials (NAATSHO). The questionnaire requested information on the FPSD systems and fall protection methods that were adopted by the DOTs for on-deck construction, maintenance or inspection work. From the 19 responses received from 17 different states, the results indicated that only two states used FPSD systems for bridge work. Four other states used active fall restraint and fall arrest systems, which are less effective methods as shown in Figure 1. More alarming was the finding that 11 of the 17 surveyed states did not reportedly use any supplementary protection beyond the existing bridge guardrail and administrative controls.

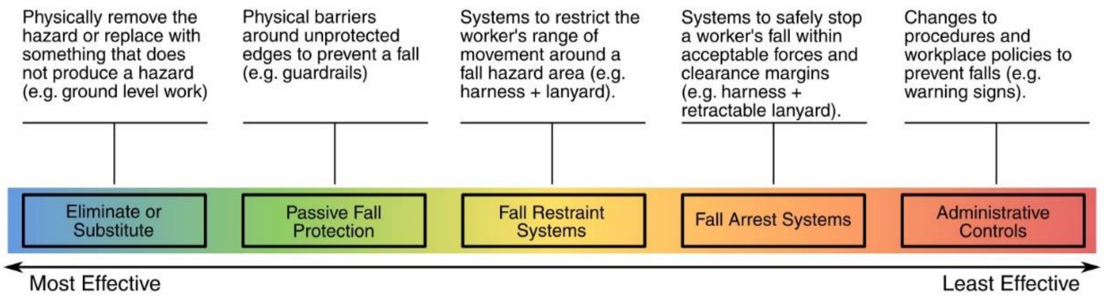


Figure 1. Hierarchy of fall protection controls (Adaptation from NIOSH 2015)

To address this nationwide safety issue, the research objective was to (1) develop a more safe, economic and efficient method for assessing compatibility using virtual prototyping, (2) identify and recommend compatible FPSDs that offer the most advantages for common bridge guardrails in the state of North Carolina, (3) conduct field studies to further evaluate the recommended FPSDs based on the utility, usability, and safety implications in the field. The results of the study is expected to yield significant benefits to NCDOT and other transportation agencies in terms of safety, cost, and work-efficiency.

BACKGROUND

To provide the necessary background and motivation for the research, the following sections describe falls in the context of bridge operations. The sections also discusses virtual prototyping which is the approach used to efficiently test compatibility between FPSDs and bridge guardrails – as will be discussed in further detail in the individual phases described in the report.

Fall Injuries and Fall Protection for Bridge Operations

Numerous efforts have been undertaken to understand and reduce fall injuries in construction. Among others, efforts have focused on understanding causal factors related to falls, development of fall prevention systems, adoption of fall prevention training programs, and the dissemination of fall prevention resources through nationwide campaigns (Bobick et al., 2010; Bunting et al., 2017; Chi et al., 2005; Dong et al., 2009; Hung et al., 2013). However, much of these efforts have focused on addressing falls in industrial, commercial, and residential projects; while only a few efforts have particularly focused on infrastructure projects such as the construction and maintenance of bridges. This has generally been the case because falls accounted for fewer injuries than the more common struck-by safety incidents caused by vehicular traffic (Bureau of Labor Statistics, 2016). Nonetheless, falls account for roughly 20% of all injuries compared to struck-by safety incidents that account for approximately 35% of all injuries among highway and bridge workers (Federal Highway Administration, 2015).

Given the recent emphasis on the nation's aging infrastructure – particularly with respect to structurally deficient and obsolete bridges – substantial investments towards bridge inspection and maintenance is expected in the next decade (American Society of Civil Engineers, 2013). For example, regulations are already in place that require the inspection of each of the nation's bridges every 24 months (Code of Federal Regulations, 2004). Because there are more than 600,000 bridges in the United States, approximately 800 bridges are being inspected on a daily basis to ensure the safety of more than 200 million daily commuters. Along with a corresponding increase in bridge inspection and maintenance work, the exposure of workers to fall-related hazards is also expected to increase.

To manage fall hazards, a variety of fall protection devices are available in the market. However, the vast majority of DOT contracts through the Federal Highway Administration include contract provisions that restrict the use of fall protection anchor points that penetrate bridge components (OSHA, 2013). Such contract provisions are generally included to protect the integrity of public bridges and guardrails; however, these requirements restrict workers from using several of the potential fall restraint and arrest systems in many practical cases.

Because of such issues, workers customarily rely on existing bridge guardrails as a barrier for their protection. However, a majority of the U.S. bridge guardrails are only 32 in. high – as opposed to the height requirement of 42 ± 3 in. set by the Occupational Safety and Health Administration (OSHA) for sufficient protection. In fact, more than 72% (i.e., 83 out of 115) of the bridge guardrails approved for use in the National Highway System fall below the regulatory minimum requirement of 39 in. (Federal Highway Administration, 2014).

To address fall protection issues, few DOTs have begun adopting supplementary devices to temporarily increase the barrier height during work. However, as discussed earlier, there are practical challenges particularly concerning compatibility between FPSD systems and bridge guardrails. Such challenges have discouraged some DOTs from adopting FPSDs in favor of less efficient alternatives. The development of more efficient compatibility testing procedures will be useful to DOTs in their efforts to protect their workforce.

Virtual Prototyping

In recent years, visualization techniques such as virtual prototyping have gained considerable popularity for various app-lications. In simple terms, virtual prototyping involves the development of a computer-generated model or prototype of a physical product (e.g. automobile engine) that is to be manufactured. The modeled virtual prototype can be assembled, manipulated, and tested in a similar fashion as would be possible with a physical prototype (Kong, 2010; Wang, 2002).

Since the advent of technologies such as computer-aided design (CAD) and computer-aided engineering (CAE), manufacturers have transitioned from using physical prototypes to virtual prototypes to conduct their design feasibility studies (Choi and Chan, 2004). The transition to virtual prototyping has offered manufacturers several benefits including the flexibility to test diverse design alternatives with substantial cost savings (Bordegoni, 2011). In particular, virtual prototyping has helped designers and product manufacturers identify complex design errors, evaluate assembly challenges, assess operational inefficiency, and also showcase the intended final product (Seth et al., 2011; Zorriassatine et al., 2003).

For example, virtual prototyping methods have been used within the automobile industry to reconstruct, design, and optimize products taking into account the ease of assembly and disassembly of components for manufacturing and maintenance operations (Dai et al., 1996; Lanzotti et al., 2015). Likewise, the aerospace industry has used virtual prototyping to iteratively design and optimize aircraft systems (Liou, 2007). Other sectors that have benefited from virtual prototyping techniques include manufacturing, healthcare, and the military (Bidanda and Bártolo, 2008; Post, 2014; Wang, 2002). More recently, techniques related to virtual prototyping (e.g., building information modeling) have been used in the construction industry to detect spatial clashes among building components and systems, detect hazards, plan site layouts, and organize construction materials and resources (Li et al., 2012; Zanen et al., 2013; Zhang et al., 2015). The benefits achieved within construction include reduction in rework requirements, reduction in assembly and planning uncertainty, improvement in safety management, and substantial cost savings (Huang et al., 2009).

While virtual prototyping has traditionally been used in the pre-manufacturing or pre-construction phases, the benefits can also be relevant for maintenance, rehabilitations and safety applications. The proposed method explores the potential use of virtual prototyping in addressing the challenges associated with the compatibility testing between FPSD systems and bridge guardrails.

STUDY APPROACH AND METHODS

The study was conducted and is organized in three different phases. The first phase focused on assessing compatibility between the marketed FPSDs and 22,000 bridge guardrails in North Carolina. This was followed by the second phase where the FPSDs that offered the most advantages from among the compatible ones were selected using the structured choosing by advantages (CBA) method. The final phase focused on field evaluation where the utility, usability, and the associated safety implications of the FPSDs were tested through field investigations. Each of these phases are organized independently in the following sections.

PHASE I: COMPATIBILITY TESTING BETWEEN FALL PROTECTION SUPPLEMENTARY DEVICES AND BRIDGE GUARDRAILS

As discussed above, only a few DOTs adopt FPSD systems for fall protection. Most DOTs choose to use alternate and less effective methods to protect their workforce from falls. This has largely been because of the challenges associated with compatibility testing – where workers physically transport and assess whether particular FPSD systems firmly attach onto specific bridge guardrails.

To facilitate the adoption of FPSDs for worker protection, we proposed a more efficient, cost-effective, and safe approach for conducting the compatibility studies. Specifically, the proposed method uses the strengths of virtual prototyping to transfer the compatibility testing into a virtual environment – where physical transportation and exposure to safety risks become unnecessary.

The proposed framework for performing the compatibility tests involves three fundamental stages. In the first two stages, design information pertaining to the bridge guardrails and the FPSD systems is gathered. This information is then used to build virtual prototypes of both the bridge guardrails and the FPSD systems in preparation for the compatibility studies. In the third stage, the virtual prototype of the FPSD system is attached to the prototype of the bridge guardrail and the compatibility is assessed. The following sections describe the compatibility testing framework in detail.

Stage I: Building the Bridge Guardrail Virtual Prototypes

In total, more than 13,000 bridges are maintained, operated, and managed by NCDOT (i.e., > 26,000 bridge guardrails). The objective of this phase was to identify those bridge guardrails that are non-compliant with the 42 ± 3 inches barrier height requirement. Therefore, the first step was to compile a database of all bridge guardrails in the state of North Carolina with a barrier height that is less than 39 inches (i.e., least acceptable height based on 42 ± 3 inches criteria) – where supplementary protection is necessary.

To create this database, the inventory of bridges and bridge guardrails maintained by NCDOT were examined and design specifications pertaining to the barrier height were extracted for all guardrails. This information was largely gathered from design drawings maintained by NCDOT. However, in cases when the design drawings were not available or maintained over the years since initial construction, the information was gathered from secondary sources including bridge inspection and maintenance reports, the AASHTO and FHWA guardrail design databases (e.g., Task Force 13 bridge railing guide), and through field measurements. Overall, more than 23,000 bridge guardrails were included in the database, suggesting that more than 88% of the guardrails in the state were non-compliant with the 42 ± 3 inches barrier height requirement.

To efficiently conduct the compatibility studies in the next phases, the bridge guardrails in the database were grouped according to their design type. For example, the Jersey barrier guardrail, shown in Figure 2(a), is the most common guardrail within the state. This bridge guardrail is present in more than 30% of the bridges in North Carolina and offers a barrier height of 32 inches. Similarly, the timber guardrail [see Figure 2(b)] is the second most common bridge guardrail in the state that is present in more than 18% of the bridges – and offers a barrier height approximately 31 inches.

(a) Jersey barrier guardrail (b) Timber guardrail

Figure 2. Sample photographs of common bridge guardrails in North Carolina.

Overall, the 13 most common guardrails that accounted for more than 22,000 bridge guardrails (i.e., 82%) were chosen for further analysis in the current study, as shown in Table 1. The remaining bridge guardrails were excluded because each of these guardrail types individually accounted for less than 1% of all the guardrails in the state. A complete analysis of the state guardrails in North Carolina is presented in Appendix A – Bridge Guardrails in North Carolina.

Using the above-mentioned data sources, the essential design specifications were extracted, and the virtual prototype built. It is important to note that only the design details that were relevant to assessing whether the FPSD system will firmly attach to the bridge guardrail were extracted. For example, non-essential design information such as the details on the embedded reinforcement within the guardrail were necessary for the purposes of the compatibility testing. After the key design specifications were extracted, virtual prototype were developed in Autodesk® Fusion 360™. Example virtual prototypes are presented in Figure 3.

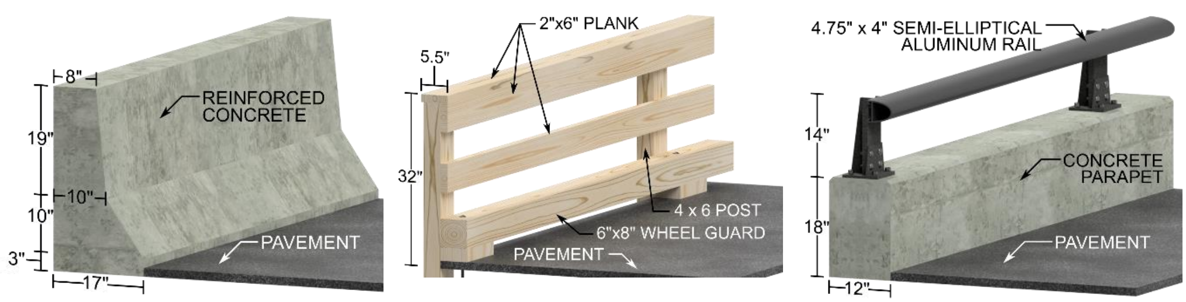
At conclusion of the modeling effort, the guardrails were reduced from 13 types to 12 types. The guardrail type 24, 1-bar concrete rail (middle) had the same geometrical characteristics as the type 11, 1-bar concrete rail (middle). Therefore, only the analysis for guardrail type 11 was completed and the reader should refer to type 11 guardrail when looking for guardrail type 24 analysis.

Table 1. Selected bridge guardrails for compatibility testing.

Guardrail Type	Count	Ranking by Count	Percentage of Total Count
04	8,306	1	30.7%
22	4,961	2	18.4%
23	1,909	3	7.1%
01	1,109	5	4.1%
25	967	6	3.6%
11	947	7	3.5%
32	826	8	3.1%
24	744	9	2.8%
02	666	10	2.5%
14	620	11	2.3%
07	423	14	1.6%
31	343	15	1.3%
33	338	16	1.3%
Subtotals	**22,159**		**82.0%**

Notes:

1. The count quantity includes both guardrails in each bridge, typically two guardrails in each bridge.
2. The geometrical characteristics of Type 11 and Type 24 guardrails are the same. Please refer to Type 11 guardrail analysis hereafter.



(a) Jersey barrier (b) Timber guardrail (c) Aluminum 1-bar

Figure 3. Virtual prototypes of bridge guardrails.

Stage II: Building FPSD Virtual Prototypes

A market analysis was conducted to identify FPSDs that are available in the United States. Using information obtained from manufacturers, product catalogs, and distributors from across the United States, more than 50 marketed FPSDs were identified. From this initial set, certain FPSDs were excluded in the current study because they required making physical alterations and structural changes to the guardrail for effective attachment – which is not desirable for the preservation of the guardrails [Occupational Safety and Health Administration (OSHA) 2013]. Similarly, freestanding FPSDs were excluded because they substantially reduced available working space.

Overall, 23 candidate FPSDs were selected for further testing. A completed list of identified FPSD is presented in Appendix B – FPSD Product Catalog

A similar approach was adopted to build the virtual prototypes of the candidate FPSDs – as was done for the bridge guardrails. First, design specifications and dimensional data for the FPSDs were gathered from design drawings and brochures made available by the manufacturers, distributors, or through the manual examination of the products. In a few cases, the manufacturers directly shared virtual prototypes of their products which were used internally for fabrication purposes.

Although similar, building the virtual prototypes of the FPSDs were more complicated than building the virtual prototypes of the bridge guardrails. Unlike the bridge guardrails that are completely static, FPSDs have moving components (e.g. adjustable clamps, removable pins, etc.) that required additional care when modeling. The virtual FPSDs were modeled accurately to replicate the dynamic and operational functionalities of the physical FPSDs. For example, the adjustable clamps in the modeled FPSDs were adjustable to the same dimensional range as would be possible with the physical FPSDs. In addition, the removal pins, tightening mechanisms, and removable elements were integrated to replicate all the features of the FPSDs. An example virtual prototype of an FPSD is shown in Figure 4. Similar to the bridge guardrails, the accuracy of the models were validated using physical measurements of a sample of FPSDs that were purchased or owned by NCDOT. In all cases, the accuracy of the models were within a 2 cm. (< 1 in.) tolerance.

(a) Exploded view

(b) Various installation configurations of the sample FPSD

Figure 4. Sample FPSD virtual prototype

Stage III: Compatibility Testing

After accurate development of the bridge guardrails and the FPSD virtual prototypes, the compatibility testing was performed. In general, the compatibility testing procedure resembled the same approach as is traditionally followed when testing is done in the real world. The only difference is that – in this case – the test is conducted in the virtual environment instead of the real environment.

The process first involved bringing both the virtual prototypes (i.e., guardrail and the FPSD system) into the same virtual space or environment followed by efforts to attach the FPSD system to the guardrail. While the assembly was performed, we operated the movable and dynamic features of the FPSD such as adjusting the clamps and tightening the bolts to assess the best possible assembly and fit. We also configured the modeling software to recognize the boundaries of the virtual components. Setting these boundaries ensured that the virtual components did not intrude or get embedded into each other like in the real world. For example, when the clamps of an FPSD firmly attach to a bridge guardrail, additional tightening to move the clamps closer was not possible.

During the virtual assembly, we assessed several factors. First, whether the FPSD attaches firmly and in a stable manner to the bridge guardrail. If this was achieved, it was concluded that the FPSD system was compatible with the specific bridge guardrail. On the other hand, if the FPSD did not firmly attach to the guardrail, we assessed if the addition of other components (e.g. lumber) allowed for the firm attachment, as shown in Figure 5. If this was achieved, it was concluded that the FPSD was compatible when the additional component was also available. If the FPSD did not firmly attach to the guardrail, the FPSD was rejected for the specific guardrail, and alternate products were evaluated. A process diagram for the compatibility testing between FPSD and bridge guardrails is presented in Figure 6.

Figure 5. Sample FPSD installation with lumber blocks

Second, if a particular FPSD system was assessed to be compatible, we evaluated if workers would be sufficiently protected from falls as per OSHA requirements by verifying whether the height requirement of 42 ± 3 inches was achieved when using the FPSD.

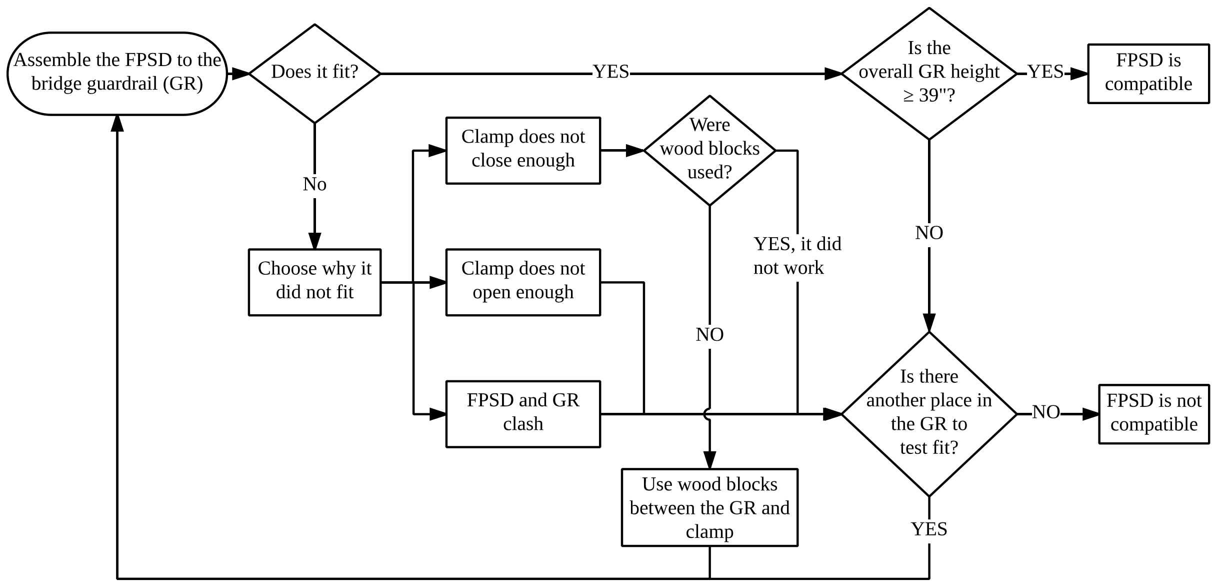


Figure 6. Process diagram for testing FPSD systems

Finally, we assessed we assess whether the use of specific FPSDs may expose workers to other safety hazards. For example, certain FPSD systems when attached to guardrails may have components extending into the work area. These components may pose a trip or struck-by hazard to workers, or may limit available work area. In addition, we assessed if the installation could be successfully performed by workers in the real world. For example, the FPSD placement location must allow workers to operate the clamping mechanism from the bridge deck without unnecessarily overreaching beyond the guardrail.

Compatibility Testing Results

The compatibility studies involved testing each of the 23 FPSDs with the 12 guardrails (i.e., 276 combinations) to identify FPSDs that can be successfully and securely attached to the guardrails. The results suggested that 11 of the candidate FPSDs (shown in Figure 7) were compatible with all 12 bridge guardrails. Brands and product names for the compatible FPSD are provided in Table 2

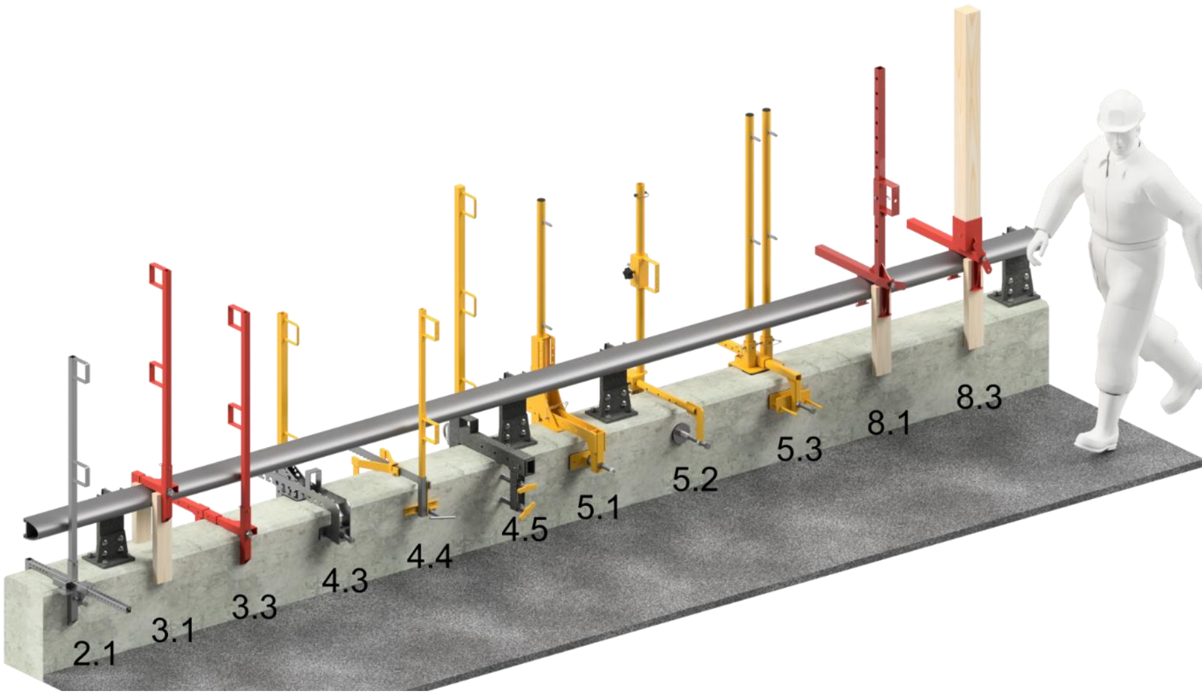


Figure 7. Compatible FPSD with bridge guardrails in North Carolina.

Table 2. Brand and product names for compatible FPSD with bridge guardrails in North Carolina

ID	Manufacturer	Product Name
2.1	DBI Sala	Flexiguard Portable Guardrail
3.1	Fall Protection Guardrails Systems	C-Clamp CC120
3.3	Fall Protection Guardrails Systems	C-Clamp MCC130
4.3	Guardian Fall Protection	Alligator Parapet Guardrail System
4.4	Guardian Fall Protection	Parapet Clamp Guardrail System
4.5	Guardian Fall Protection	Parapet Anchor
5.1	AES Raptor	RaptorRail
5.2	AES Raptor	All-in-One
5.3	AES Raptor	Universal Guardrail Parapet Clamp
8.1	Ellis Manufacturing	Parapet Guardrail GRS-P12
8.2	Ellis Manufacturing	QuickRail Parapet Guardrail QR-P12

An in-depth analysis of the compatibility testing that includes renderings and fit information is provided in Appendix C – . In addition, A summary booklet of the compatibility testing studies is presented in Appendix D – Field Guide Booklet

To ensure that the results of the virtual compatibility studies were accurate and valid, representative FPSDs from the 11 compatible alternatives were physically tested with 4 different guardrail types. An illustrative example comparing the virtual compatibility studies against the physical testing is shown in Figure 8 and Figure 9. Similar to the presented examples, the physical tests replicated the findings of the virtual compatibility studies in all cases.

(a) RB-02. FPSD owned by NCDOT (b) UGPC over rail (c) UGPC over parapet

Figure 8. Validation testing for aluminum 1-bar guardrail (Type 01).
UGPC: Universal Guardrail Parapet Clamp

(a) RB-02. FPSD owned by NCDOT (b) UGPC over post and beam width (c) UGPC over beam width (d) UGPC over beam depth

Figure 9. Validation testing for thrie beam guardrail (Type 25).
UGPC: Universal Guardrail Parapet Clamp

PHASE II: SELECTION OF COMPATIBLE FALL PROTECTION SUPPLEMENTARY DEVICES

As discussed above, the results of the compatibility testing yielded 11 FPSDs that were compatible with each of the 12 bridge guardrails. The next step in the study was to assist NCDOT identify FPSDs that offered the most advantages – from the 11 compatible alternatives – to maximize safety, productivity, and work efficiency. Therefore, this phase of the study focused on identifying desirable characteristics, identifying the selection criteria, and using the decision-making method Choosing by Advantages (CBA) for selecting the FPSDs that offer the most advantages.

Stage I: Identifying Desirable Characteristics and Selection Criteria for FPSDs

The desirable characteristics were identified in two stages. In the first stage, interviews were held with 8 bridge workers and 3 supervisors that used FPSDs regularly in the field. The workers and the supervisors had accumulated over 75 years of experience in construction and bridge maintenance work. In the second stage, a brainstorming session was conducted with an expert panel of 9 NCDOT professionals representing the fall protection committee within the safety and risk management unit. In total, the expert panel had gathered over 200 years of experience in areas including construction, maintenance, and safety management. Several of the professionals were Certified Safety Professionals (CSPs), Managers of Environmental Safety and Health (MESH), and professional trainers. The expert panel also reviewed and finalized the desirable characteristics identified in the two stages.

The process yielded several items that were grouped under 7 factors with the help of the expert panel. Table 3 presents the identified factors along with a brief description. Next, the expert panel reviewed the desirable characteristics in Table 3 to identify the decision criteria that must be used to compare the FPSDs. Based on the review, the expert panel first categorized the factors into two groups – *Must* and *Want* factors – as shown in Table 4. *Must* factors are required or mandatory specifications that the FPSDs must satisfy for successful adaptation in practice. For example, as shown in Table 4, any FPSD that does not comply with the OSHA strength requirements cannot be adopted in practice; and will need to be excluded from further analysis based on the identified criteria. On the other hand, the *want* factors are preference specifications that will be used to make relative comparisons between the potential FPSDs. For example, as shown in Table 4, *ease of transportation and installation* was categorized as a *want* factor, and FPSDs that are easier to transport, load, unload, assemble, install and remove were preferable according to the decision criteria.

After the decision criteria were identified, the expert panel decided that the associated measures (i.e., attributes) for objectively quantifiable factors (e.g., s*elf-weight of the FPSD, protrusion into the work area)* will be obtained from previously gathered product specifications, design drawings, physical measurements, or measurements of the virtual prototypes. On the other hand, the expert panel decided that the more subjective and relatively difficult to measures factors (e.g., *ease of transportation and installation* and *exposure to the unprotected edge*) will be quantified using a subjective scale ranging from 1 to 10 based on input from the expert panel, as shown in Table 4.

Table 3. Desirable characteristics of FPSDs

Factors	Brief Description
Compliance with OSHA's strength requirement.	The manufacturer must have testing records certifying that the FPSDs are capable of withstanding, without failure, a force of at least 200 lb. applied in any outward or downward direction along the top edge (29 CFR §1926.502(b)(3)) to provide sufficient protection.
Adjustable spacing between FPSD posts	When the spacing between individual FPSDs are adjustable (i.e., not fixed by design), the workers will be able to flexibly place the FPSDs posts in desirable locations (within manufacturer's spacing recommendations) along the bridge guardrail to avoid clashes or conflicts with other guardrail components.
Ease of transportation and installation	Workers must be able to easily, efficiently, and quickly assemble, install, and remove FPSDs during bridge maintenance tasks. In addition, workers must be able to efficiently transport the FPSDs between the storage and work locations. This factor excludes self-weight of the FPSDs which may also affect ease of installation and mobility.
Protrusion into the work area	Certain FPSDs have elements that protrude or intrude into the work area after installation on the guardrail. This often reduces the available workspace for workers and is associated with a higher number of struck-against safety incidents.
Exposure to the unprotected edge	When workers are required to overextend beyond the bridge guardrail over the unprotected edge to install the FPSDs, the likelihood of falls from the bridge deck increases. FPSDs that require no or minimal overextension are preferable.
Self-weight of the FPSDs	The weight of the FPSDs can substantially affect work efficiency, productivity, and safety. Lighter FPSDs makes the transportation, installation, and removal of FPSDs easier and quicker. In addition, manual handling of heavy FPSDs can lead to overexertion injuries among bridge workers.
Number of individual components and movable parts required for installation	FPSDs have a number of components or individual parts that are needed for the installation. These include dimensional lumber, supplementary posts, connector sleeves, pins, and others. When a larger number of components or parts are needed or must be operated during installation, the installation process is generally more involved and time consuming. In addition, when additional components are needed, the likelihood of losing one of them increases, which can cause delays or render the FPSD unusable.

Table 4. Decision criteria and measures for comparing FPSDs

Factors	Decision Criteria & Measure
***Must* Factors:**	
Compliance with OSHA's strength requirement	Required
Adjustable spacing between FPSD posts	Required
***Want* Factors:**	
Ease of transportation and installation	**Easier is better.** Measured using a scale ranging from 1 to 10. A score of 1 is assigned when the transportation, loading / unloading, assembly, installation, and removal of the FPSDs can be easily, efficiently, and quickly performed without additional tools, with a minimum number of steps, and by a single worker. A score of 10 is assigned when the transportation, loading / unloading, assembly, installation, and removal of the FPSDs is cumbersome, slow, requires a large number of steps, and may require two or more workers.
Protrusion into the work area	**Lesser is better.** Measured as the protrusion length in inches.
Exposure to the unprotected edge	**Lesser is better.** Measured using a scale ranging from 1 to 10. A score of 1 is assigned when the assembly and installation of the FPSD will not require the workers to overextend beyond the bridge guardrail over the unprotected edge. A score of 10 is assigned when workers will have to spend considerable time overextending beyond the bridge guardrail during the FPSD assembly, installation and removal.
Self-weight of the FPSD	**Lesser is better.** Measured as the weight in pounds.
Number of individual components and movable parts required for installation	**Lesser is better.** Count of the number of unique parts or FPSD components that must be operated to complete the FPSD assembly and installation.

Using such a subjective scale is a deviation from the traditional CBA method where measures or attribute characteristics are generally verbalized prior to assessing the advantages. However, the diverse nature of the FPSDs, the large number of examined FPSD alternatives, and the unique challenges associated with the different FPSDs were expected to yield abstract verbal descriptions (e.g., complex clamping mechanism that is difficult to operate, operation of multiple clamps and placement of multiple pins during installation, installation requires physically holding FPSD in place while the pins are inserted simultaneously) that would not be easy to compare when the relative advantages of candidate FPSDs are to be assessed. Therefore, the subjective scale, although not customarily used, was preferred for the current study by the expert panel.

Prior to initiating the CBA procedure in the next phase, each of the 11 FPSDs were evaluated for compliance with the 2 *must* (i.e., mandatory) factors. When the information was not available in the product catalogs or brochures, specifications from the manufacturers and the distributors were requested. The evaluation indicated that all the 11 FPSDs complied with the *must* factor requirements. Therefore, all the 11 FPSDs were compared based on the *want* factors in the next phase using the CBA procedure.

Stage II: Choosing by Advantages (CBA) Workshop with NCDOT Expert Panel

In recent years, the CBA decision-making method has gained considerable popularity as a collaborative, transparent, and reliable decision-making approach. For example, the CBA method has been used for various construction applications including choosing among sustainable building materials (Arroyo et al. 2016a), selecting sustainable building systems (Arroyo et al. 2016b), comparing conceptual building design alternatives (Kpamma et al. 2015), and prioritizing efficient formwork systems (Martinez et al. 2016). Because CBA offers a structured approach to compare possible alternatives (e.g., FPSDs) based on their advantages (i.e., beneficial differences), the CBA method was adopted for the current study (Suhr 1999).

As a first step, this phase focused on identifying the preferred FPSDs for the *Aluminum 1-Bar Metal Guardrail* (Type 01) shown in Figure 3(c). This particular guardrail was selected because of its distinctive structural shape that presented unique challenges for the installation of FPSDs. Therefore, the objective was to compare the 11 FPSD alternatives identified in Phase III using desirable characteristics (referred to as *factors* in the CBA literature) for the *Aluminum 1-Bar Metal Guardrail* in particular.

To efficiently accomplish the objectives of this phase, the expert panel members were invited to a half-day CBA workshop in a 360° visualization studio located at North Carolina State University. The equipment in the visualization lab included 12 projectors to display high fidelity digital data across the four walls of the visualization studio. The facility provided an effective means to display CBA related templates, visualize and operate virtual prototypes that were constructed in Phase II, and virtually demonstrate the installation of the FPSDs on the guardrail. Figure 10 presents a panoramic view of the visualization studio captured during the session. As can be seen, the screen on the left was used to record the data generated during the CBA session. The other three screens were used to present videos demonstrating the installation of FPSDs on the guardrail, final renderings of the installed FPSDs, and the virtual assembly of the FPSDs and the guardrail in Autodesk® Fusion 360™ that could be operated as needed to examine particular details.

At the beginning of the workshop, an update on the research progress to-date was provided, and the expert panel members were introduced to the CBA procedure. To ensure the proper understanding of the CBA method, an illustrative decision-making example adopted from Suhr (1999) was provided.

To capture the data from the CBA session, the CBA tabular template shown in Figure 11 was adopted and presented in one of the walls in the visualization lab (see Figure 10). At this stage, the template only included the factors and criteria in the left-most column (including the titles: "Attribute" and "Advantage"), and the 11 FPSDs in the top row. The other details were completed as the session proceeded through the following three tasks.

Figure 10. Panoramic view of the 360° visualization studio

Task 1: Describing and quantifying the FPSD attributes

In the first task, the expert panel focused on identifying the attributes of each FPSD alternative using the measures discussed earlier. For factors involving subjective measures (i.e., *ease of transportation and installation* and *exposure to unprotected edge*), the step-by-step installation videos that were created using the virtual prototypes were reviewed. In addition, whenever necessary, the virtual prototypes in the Autodesk® Fusion 360™ environment were examined for particular details. Subsequently, each member of the expert panel made individual evaluations for the subjective factors for each FPSD. After the individual evaluations were complete, the evaluations were shared among the expert panel members, and the panel collaboratively decided on the final attributes for each FPSDs. When dissenting evaluations were received from particular members, the rationale behind the evaluation was presented by the dissenting member, and discussions followed until consensus was achieved.

For objective measures (i.e., *protrusion into the work area*, *number of individual components and movable parts*, and *self-weight of the FPSDs*), as discussed earlier, the information was obtained from previously gathered product specifications, design drawings, physical measurements, or measurements of the virtual assembly. Figure 11 summarizes the attribute descriptions that were assigned to each FPSD system at the conclusion of Task 1.

Task 2: Assessing the advantages of the FPSD alternatives

As previously mentioned, the strength of CBA over traditional decision-making methods is the structured approach that is used to compare the advantages or the beneficial differences between the alternatives (i.e., FPSDs). Therefore, Task 2 focused on quantifying the relative advantages of the FPSDs. The first step for this task was to identify the least preferred attribute for each factor. For example, for the *ease of transportation and installation* factor that was described using the subjective scale ranging between 1 and 10, the least preferred attribute is provided by the FPSD identified as Alternative 11 (i.e., score of 10). The least preferred attribute for each of the factors were similarly identified and highlighted in red color as shown in Figure 11.

Next, the advantage of each FPSD alternative compared to the least preferred attribute for each factor was used to decide the advantage. For example, the FPSD labeled as Alternative 1 offers a

7-units advantage (i.e., the difference between the attribute ratings of alternate 11 and 1) over the least preferred attribute for the *ease of transportation and installation* factor. Figure 11 presents the advantages of each FPSD for each factor highlighted with a blue background.

Task 3: Deciding the importance of each advantage

Rather than comparing the advantages themselves, CBA facilitates decision making where the importance or the value-derived from the advantages are compared. Therefore, in Task 3, the expert panel members examined the advantages to assess their relative importance.

As a first step, the largest advantage for each factor was identified and marked using a green circle as shown in Figure 11. Next, the largest advantages for each factor were compared by the expert panel members to identify the paramount advantage – or the advantage that offers the greatest value in their perspective. The experts agreed that the 8-unit *easier to transport and install* advantage of Alternative 3 offered the paramount advantage. Accordingly, the paramount advantage was assigned a relative importance score of 100 in a scale from 1 to 100 (shown in bold in Figure 11). Subsequently, the expert panel assessed the importance of the remaining four largest advantages (i.e., those highlighted by the green circles) relative to the paramount advantage.

In the next step, the importance of the smallest advantage (over the least preferred attribute) for each factor was assessed relative to the importance of the advantages previously recorded. For example, the FPSD identified as Alternative 8 was *easier to transport and install* by 1-unit (i.e., advantage) than Alternative 11 which was the least preferred attribute. In this case, the expert panel members assigned a relative importance of 10 for this 1-unit advantage.

At this stage, the importance of the largest advantage and the smallest advantage for each of the factors were available. For example, for the *ease of transportation and installation factor*, the largest advantage was assigned an importance of 100 (also identified as the paramount advantage) and the smallest advantage was assigned an importance of 10 as shown in Figure 11. For efficiency, the importance of the remaining advantages across each factor was computed using the linear interpolation function as shown in Equation 1.

$$I_{ij} = I_{Lj} + \left(A_{ij} - A_{Lj}\right)\left(\frac{I_{Uj} - I_{Lj}}{A_{Uj} - A_{Lj}}\right) \quad (1)$$

Where I_{ij} = importance of the advantage for alternative i in factor j; A_{ij} = advantage for alternative i in factor j; A_{Lj} and A_{Uj} = smallest and the largest advantage in factor j, respectively; I_{Lj} and I_{Uj} = importance of smallest and the largest advantage in factor j, respectively.

Finally, the aggregate importance of advantages offered by each FPSD was calculated as the sum of all the importance of advantages across the factors. In accordance with the CBA methodology, the alternative that offers the highest aggregate importance of advantages is the most preferred alternative.

Factor / Criteria		2.1 Flexiguard	Importance	3.1 CC-120		3.3 MCC-130		4.3 Alligator		4.4 Par. Clamp		4.5 Par. Anchor		5.1 RaptorRail		5.2 All-in-One		5.3 UGPC		8.1 GRS-P12		8.3 QR-P12	
Factor: Ease of transportation and installation. **Criteria:** Easier is better. 1 is very easy to install and transport, and 10 is very hard to transport and install.	**Attribute:**	3		8		2		7		7		2		4		9		5		8		10	
	Advantage:	7-units easier	87	2-units easier	23	8-units easier	**100**	3-units easier	36	3-units easier	36	8-units easier	100	6-units easier	74	1-units easier	10	5-units easier	61	2-units easier	23		
Factor: Exposure to unprotected edge. **Criteria:** Lesser is better. 1 represents minimal exposure to fall hazards and 10 very exposed to fall hazards.	**Attribute:**	2		8		2		8		2		7		7		9		4		2		5	
	Advantage:	7-units less exposure	85	1-units less exposure	10	7-units less exposure	85	1-units less exposure	10	7-units less exposure	85	2-units less exposure	23	2-units less exposure	23			5-units less exposure	60	7-units less exposure	85	4-units less exposure	48
Factor: Protrusion into the work area. **Criteria:** Lesser protrusion is better. Measured in inches.	**Attribute:**	18		4		2.25		6.5		7		9		8.75		8.75		8.75		4.25		4.5	
	Advantage:			14 inches less protrusion	77	15.75 inches less protrusion	90	11.5 inches less protrusion	59	11 inches less protrusion	55	9 inches less protrusion	40	9.25 inches less protrusion	42	9.25 inches less protrusion	42	9.25 inches less protrusion	42	13.75 inches less protrusion	75	13.5 inches less protrusion	73
Factor: Number of individual components and movable parts. **Criteria:** Lesser parts is better.	**Attribute:**	4		5		5		6		4		4		5		6		5		4		7	
	Advantage:	3 fewer parts	60	2 fewer parts	40	2 fewer parts	40	1 fewer parts	20	3 fewer parts	60	3 fewer parts	60	2 fewer parts	40	1 fewer parts	20	2 fewer parts	40	3 fewer parts	60		
Factor: Self-weight. **Criteria:** Lighter is better. Measured in pounds.	**Attribute:**	18		13		15		42		38		33		37		25		37		23		19	
	Advantage:	24 pounds lighter	66	29 pounds lighter	80	27 pounds lighter	74			4 pounds lighter	10	9 pounds lighter	24	5 pounds lighter	13	17 pounds lighter	46	5 pounds lighter	13	19 pounds lighter	52	23 pounds lighter	63
Aggregate importance of advantages:			298		230		**389**		124		246		247		191		118		216		295		184

Figure 11. CBA tabular template used for data collection

Stage III: Choosing by Advantages (CBA) Applied to all Guardrails

The previous phase focused on identifying the preferable FPSD for the *Aluminum 1-Bar Metal* Guardrail. The current phase followed a similar approach to identify the preferred FPSD for all the guardrails using the CBA tabular method form.

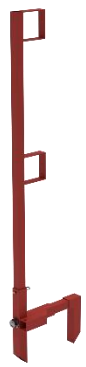
Based on consultation with the expert panel, it was decided that the CBA tabular method used for the *Aluminum 1-Bar Metal* Guardrail would be adjusted as needed to create 11 additional independent CBA tables corresponding to each guardrail. More specifically, using the completed tabular form shown in Figure 11, adjustments were made to the attributes, advantages, and the importance of the advantages for each guardrail. This was an efficient method to gather the large amount of data because certain attributes, advantages, and their importance remained unchanged irrespective of the guardrail in consideration (e.g., self-weight) – and the procedure resulted in substantial time savings.

After the necessary changes were incorporated, the expert panel once again revisited the 12 completed tabular forms (i.e., corresponding to each guardrail) for a final review. In this stage, minor revisions to the importance of advantages were made by comparing the attributes across the guardrails. This provided an opportunity for the expert panel to discuss the relative importance of the attributes in light of the differences in the guardrail types. After the importance of advantages were finalized and consensus was achieved, the aggregate importance score for each of the FPSDs in all 12 guardrails were calculated similar to Phase IV. The revised CBA tables are presented in Appendix E – Choosing by Advantages (CBA) Summary Tables.

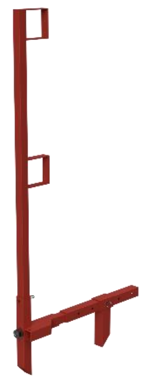
Results

The CBA method was adopted to identify FPSDs that offered the most advantages for each bridge guardrail. The process yielded 660 evaluation ratings (12 bridge guardrails x 11 FPSDs x 5 want factors) that were gathered from an expert panel representing NCDOT. Using the CBA tabular form presented in Figure 11, the aggregate importance of advantages for each of the FPSDs were computed for the 12 guardrails. The summary of the aggregate importance of advantages for each of the FPSDs corresponding to each bridge guardrail is presented in Table 5.

Based on the results, the 3 most suitable FPSD devices for NCDOT bridge maintenance and inspection work were identified as show in Figure 12.



Fall Protection Guardrail Systems
Model CC120



Fall Protection Guardrail Systems
Model MCC130

Ellis Manufacturing
Model GRS-P12

Figure 12. Recommended FPSD devices for North Carolina Bridges.

Table 5. Summary of aggregate importance of advantages for the FPSDs

	FPSD ID										
Guardrail Type	**2.1**	**3.1**	**3.3**	**4.3**	**4.4**	**4.5**	**5.1**	**5.2**	**5.3**	**8.1**	**8.3**
01 – 1-Bar Aluminum	316	247	380	161	245	270	224	185	239	283	213
02 – 1-Bar Concrete Top # 1	358	406	380	195	272	254	224	197	252	363	239
04 – Jersey Barrier	313	403	377	181	270	244	221	196	250	361	236
07 – 1-Bar Concrete Top # 2	358	406	380	196	271	250	224	197	252	363	239
11 – 1-Bar Concrete Middle # 1	358	406	380	196	271	244	225	198	252	363	239
14 – 1-bar Concrete Middle # 2	339	361	336	186	253	231	215	187	215	344	192
22 – Wooden Guardrail	181	275	249	129	167	160	153	155	166	245	182
23 – W-Beam	164	285	259	71	110	165	157	185	169	255	223
25 – Thrie Beam	215	303	278	71	120	166	224	210	189	274	214
31 – Concrete Church Window	358	406	380	196	271	247	224	197	252	363	239
32 – Tubular Thrie-Beam	226	317	291	142	120	186	224	210	194	279	219
33 – Tubular Thrie-Beam Retrofit	245	336	310	189	195	232	271	276	232	298	247
Cumulative aggregate importance of advantages	3431	4150	4001	1912	2566	2649	2586	2393	2663	3792	2682
Rank	4	1	2	11	9	7	8	10	6	3	5

PHASE III: FIELD TESTING OF FALL PROTECTION SUPPLEMENTARY DEVICES USING WEARABLE TECHNOLOGY

Prior to making the final recommendations to NCDOT, field tests were conducted to further evaluate the FPSDs. The field tests focused on evaluating the FPSDs based on empirical and physiological data gathered from the field. The field tests focused on evaluating the physical demand and ergonomic risk captured using wearable devices, time necessary for the installation of the FPSD systems, and the perceived utility and usability of the FPSD systems for practical work scenarios. The work scenarios considered as part of the study included (1) installation, (2) uninstallation, (3) loading, and (4) dismantling to simulate activities involving FPSDs at bridge locations and during storage, preparation, and transportation. The below sections describe the experimental approach and the findings.

Experimental Procedures

Six field experiments intended to replicate the procedures of using FPSDs were conducted to compare four commercially-available FPSD systems, shown in Figure 13. During each experiment, the procedures intended to replicate the loading and unloading activities that occur during preparatory activities prior to initiating work (e.g., at the storage yard, at bridge arrival), as well as the installation and dismantling activities of the FPSDs at actual bridge sites with guardrails that are non-compliant with the 42 ± 3 inches height requirements.

(a) CC-120 Weight: 13 lbs. (b) MCC-130 Weight: 15 lbs. (c) ParaClamp Weight: 25 lbs. (d) RaptorRail Weight: 32 lbs.

Figure 13. FPSDs tested in this Study

Each field experiment was completed in coordination with bridge maintenance engineers and supervisors from the North Carolina Department of Transportation (NCDOT). The supervisory personnel also helped with the recruitment of the participant workers from whom data was collected. In total, six bridge maintenance workers participated in this experimental effort. All participants were healthy males between the ages of 30 and 60, with 6to 20 years of bridge maintenance experience. In addition, the workers were familiar with the use and installation of FPSDs. All participants provided written consent, physical information, and were informed about the potential risks of this study. The Institutional Review Board of North Carolina State University approved the procedures of this study.

Loading and Unloading Activities

This part of the experiment intended to replicate the loading and unloading activities performed in preparation for bridge maintenance activities (i.e. loading of FPSD), at bridge arrival (i.e. unloading), at completion of bridge work (i.e. loading), and at conclusion of the work day (i.e. unloading). When practical, these experiments were completed at NCDOT's storage yard to minimize the workers' and researchers' exposure to traffic and fall-related hazards, as well as minimize the inconveniences caused to vehicle drivers and pedestrians due to partial bridge closures while completing the experiments on the bridge deck.

To begin each loading experiment, the worker was asked to rest by sitting in a chair next to the work vehicle (i.e. pickup truck) while the researchers and non-active participant workers and supervisors placed the FPSD system 25 feet away from the work vehicle, as shown on Figure 14. Following this, the worker was tasked with loading the FPSD system onto the work vehicle as normally completed in preparation for bridge work. Data collection began when the worker started walking towards the FPSD system and concluded when all the FPSD components were loaded on the work vehicle.

After taking a 4-minute seating break to bring the physiological levels to normal conditions, the worker was tasked to unload the previously-loaded FPSD system from the work vehicle and lay all the objects as normally done prior to the installation of the FPSD system on to a bridge guardrail; that is, alongside the bridge guardrail, as depicted in Figure 15. Data collection began when the worker began walking towards the work vehicle and concluded when the last object (i.e. post or rail) was placed on the ground.

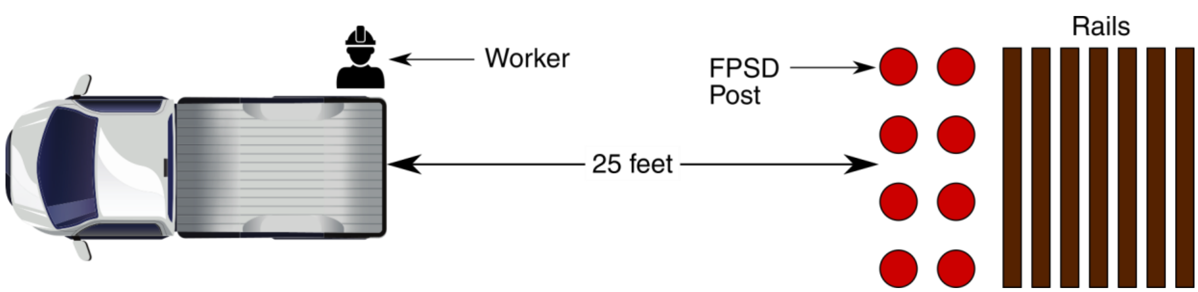


Figure 14. Schematic layout of FPSD system prior to loading activities.

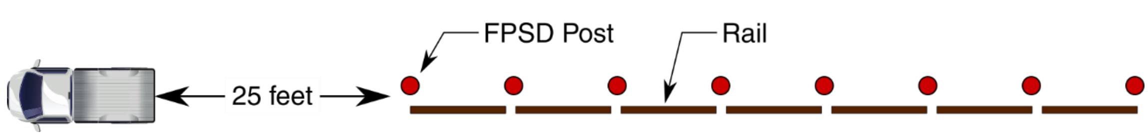


Figure 15. Schematic layout of objects at conclusion of unloading activities.

Installation and Dismantling Activities

This part of the experimental procedure consisted of the sequential installation and dismantling of each of the 4 FPSD systems. Installation and dismantling activities were completed at three bridge sites with low-height guardrails where NCDOT frequently install FPSDs to provide sufficient fall protection to the workforce. In collaboration with NCDOT officials, the researchers selected bridge sites that 1) had low-height guardrail design frequently encountered in bridges across the state, 2) offered convenient locations to the available work crews, and 3) had the lowest possible vehicular traffic volumes through and underneath (when applicable) the bridge.

At bridge arrival, NCDOT placed all required work zone safety measures, including lane closures and traffic controls. Prior to data collection, the FPSD system to be tested was unloaded from the work vehicle and placed along the bridge guardrail, as shown in Figure 16. Before each activity (installation and dismantling), the worker took a 4-minute sitting break to bring the physiological levels to resting conditions. The installation activity consisted of lifting, placing over the guardrail, and tightening the FPSD posts onto the guardrail. The dismantling activity consisted of loosening the tightening mechanism, lifting, and placing the FPSD posts on the bridge deck. In both cases, data collection began when the worker stood up from the sitting break and concluded when the activity was completed for all the FPSD's posts.

Figure 16. Preparation for Installation Activities

Data Collection Methods

Two methods of data collection were used for the field studies. First, wearable devices were worn by the participant workers to collect physiological and motion data. Second, a survey questionnaire was completed by the participant workers at conclusion of each experiment to collect data regarding the utility and the usability of the FPSD systems.

The Zephyr BioHarness™ 3 wearable device was used to gather physiological and motion data from the participants as they completed the experimental activities. This wearable device was chosen for its ability to accurately and unobtrusively capture heart rate (HR), breathing rate (BR), and 3-axis thoracic accelerations. The Zephyr BioHarness™ has been successfully used in the past to evaluate physical strain of construction tasks (Gatti et al. 2012), as part of an experimental worker real-time monitoring systems (Cheng et al. 2013), and to monitor roofing workers on-duty and off-duty activities (Lee et al. 2017a). More recently, this wearable device was validated as an instrument that provides reliable and valid measurements of the heart rate (Nazari et al. 2018) and trunk flexions (Lee et al. 2017b).

Workers' Physiological or Physical Demand

Among methods to estimate physiological demands, heart rate monitoring has been validated as one of the most efficient and cost-effective methods (Freedson and Miller 2000; Keytel et al. 2005; Spurr et al. 1988). As a result, heart rate monitoring has been extensively used in recent construction research (Aryal et al. 2017; Awolusi et al. 2018; Lee et al. 2017a). Heart rate is positively correlated with physiological demands, meaning that elevated heart rates are an indication of physically demanding activities that lead to greater levels of energy expenditure. Therefore, the heart rate data was used an indicator of the level of physiological strain from each FPSD as the participants completed the experimental activities.

To precisely measure the changes in the heart rate due to the experimental tasks, we used a differential heart rate measurement $(DiffHR)$, calculated as the difference between the mean heart rate of the 60 seconds preceding the start time (t) of the activity – while the worker was resting – and the mean heart rate of the worker while completing the experimental activity; that is from start time (t) to completion time (T).

Workers' Postural Assessments

Work Related Musculoskeletal Disorders (WMSDs) in the U.S. construction sector remains well above the average for all other industries. In fact, the back is the most-frequently reported body part in non-fatal injuries causing days away from work (CPWR – The Center for Construction Research and Training 2018). Therefore, reducing the risk factors associated with the manual handling of equipment and materials is an effective measure to reduce back injuries and WMSDs. Among the factors that increase the biomechanical loading of the spine are non-neutral trunk postures (i.e. back bending). Bending, rotation, and twisting of the trunk postures increase the moment located at the lower back, effectively increasing the muscular forces required to counteract the moment and to maintain the body in a stable position. In turn, the compressive and shear forces to the spine increase (Brauer 2016; National Research Council and the Institute of Medicine 2001).

The Zephyr BioHarness™ records the vertical (X), lateral (Y), and sagittal (Z) accelerations in gravity units, as shown in Figure 17. Based on these accelerations, the sagittal thoracic bending angle (forward or backward movement) and lateral thoracic bending angle (left or right movement) were computed using Equation (2) and Equation (3) respectively. To account for the individual differences of the workers' torso and the wearable's fit, posture correction factors were obtained by asking each worker to stand steady in a neutral upright position for 30 seconds before beginning of the experimental activities. Without such correction factor, the values obtained from the wearable may not truly indicate a neutral upright position. After correcting the posture data by subtracting or adding the correction factors as appropriate (both sagittal and lateral), a compound torso angle γ was calculated as the addition of the absolute values of the sagittal and lateral bending angles, as shown in Equation (4).

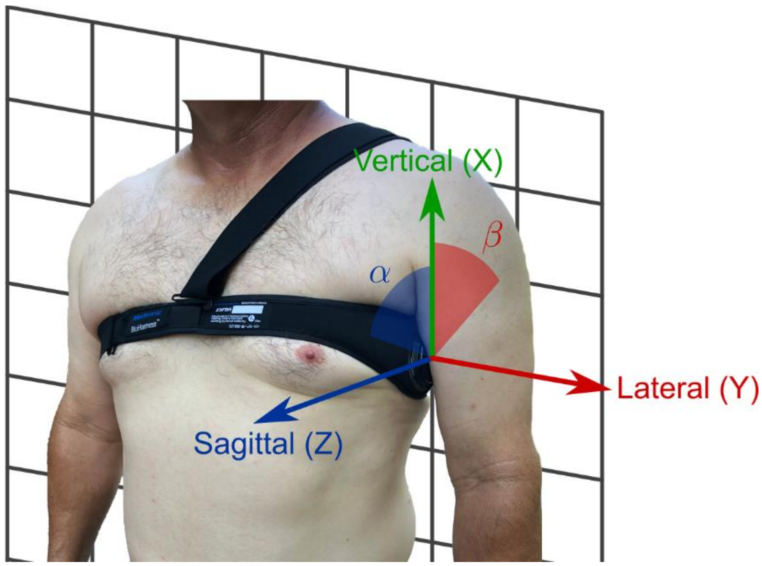


Figure 17. Wearable Placement and Accelerometer Axis Orientation.

$$\text{Sagittal Angle } (\alpha)^\circ = \tan^{-1}\left(\frac{Z}{\sqrt{X^2+Y^2}}\right)\left(\frac{180^\circ}{\pi}\right) \quad (2)$$

$$\text{Lateral Angle } (\beta)^\circ = \tan^{-1}\left(\frac{Y}{\sqrt{X^2+Z^2}}\right)\left(\frac{180^\circ}{\pi}\right) \quad (3)$$

$$\text{Compound Angle } (\gamma)^\circ = |\alpha^\circ| + |\beta^\circ| \quad (4)$$

Utility and Usability studies

The utility and the usability of the safety devices are important factors that must be considered while evaluating potential solutions (Cameron et al. 2007; Johnson et al. 1998). Therefore, utility and usability data were gathered using a survey instrument from the participant workers after completion of the experimental activities. The survey questionnaire was designed to capture demographic information (i.e., gender, age, years of experience, and previous experience with FPSDs) and the workers' perceptions about each of the 4 FPSDs by evaluating their level of agreement with 15 survey items using a 7-point Likert scale (1 for strong disagreement and 7 for strong agreement). The complete survey instruments is shown in Appendix F – Field Survey Questionnaire.

The survey instrument was designed using the data collected during the previous decision-making stage of this study in which an expert panel of 9 transportation professionals belonging to the Fall Protection Committee within the Safety and Risk Management Unit from NCDOT participated. The survey questionnaire was reviewed and confirmed by members of the Committee as appropriate to accurately capture the worker's perception with regards to utility and usability.

Table 6. Survey questionnaire statements evaluating the FPSDs

Survey Items
1. The FPSD feels lightweight and its installation and uninstallation requires acceptable physical effort (i.e., does not require overexertion).
2. The FPSD is easy to install and uninstall to and from the guardrail.
3. The FPSD can be quickly installed and uninstalled to and from the guardrail.
4. The FPSD is compact and requires minimal storage space in the yard/warehouse.
5. Learning to use the FPSD is quick, intuitive, and does not require extensive instruction.
6. The installed FPSD does not interfere with bridge maintenance and inspection operations.
7. The FPSD is easy to load and unload from work vehicles and to carry around the work area.
8. The FPSD appears durable, sturdy, and requires minimal maintenance.
9. The FPSD requires minimal preparation before installation.
10. When installed, the FPSD does not increase the likelihood of struck-against incidents (i.e. protrusion into the work area).
11. The installation does not require me to overextend beyond the bridge guardrail.
12. The installation does not require me to be in uncomfortable postures (e.g. kneeling, bending) for extended time periods.
13. The risk of hand injuries while handling the FPSD is minimal (e.g., cuts from sharp ends, pinch points).
14. The FPSD effectively reduces the risk of falls from bridge decks.
15. I would recommend the use of this FPSD during bridge work.

Results

A total of six field experiments were conducted using wearables devices as workers completed four activities (loading, unloading, installation, and dismantling) with four different FPSDs, totaling 96 trials. In addition, at the conclusion of the experimental procedures, each of the six participant workers completed the questionnaire survey to assess the utility and the usability of the individual systems.

The purpose of the assessment was to evaluate whether there was a difference in the (1) mean differential heart rate to assess physiological demand, (2) the mean compound torso angle for postural assessment, and (3) the mean installation time. Based on the findings, the most desirable FPSDs can be identified and recommendations can be made to maximize safety, productivity, and work efficiency.

To make such comparisons, the analysis of variance (ANOVA) statistical approach was adopted. The above mentioned measures of interests were treated independently as the response variables in separate analyses and the four FPSDs were modelled as the independent variable or as the fixed effect. The effect of the task (i.e., load, unload, install, and dismantle) and the individual workers were modelled as a block variable since the differences in the responses across the tasks or the workers was not of interest. More specifically, the research question that was of interest was to only identify particular FPSDs based on the differences in the response variable when irrespective of the particular task or the participating workers. Finally, the Tukey post-hoc analysis procedure was adopted to make pairwise comparisons and assess differences between the individual FPSDs.

The survey questionnaire data was analyzed using the nonparametric Friedman ANOVA test followed by post-hoc analysis.

Differential Heart Rate

The response variable *DiffHR* for all 96 activities were calculated as the difference between the mean heart rate of the 60 seconds preceding the activity start time and the mean heart rate of the worker throughout the duration the experimental activity when performing a particular task using a given FPSD. Therefore, the *DiffHR* captures the physiological exertion associated with the use of the FPSD.

The descriptive statistics for each of the FPSDs are presented in Table 7 and the ANOVA results are presented in Table 8. As can be seen, the ANOVA results suggests that the *DiffHR* associated with the FPSDs were not equal [F (3,84) = 3.680, p = 0.015].

Table 7. Descriptive Statistics for Differential Heart Rate

	FPSD			
	RaptorRail	CC120	MCC130	ParaClamp
Median	27.21	21.96	25.31	24.00
Mean	26.65	22.17	24.26	23.29
Std. Dev	5.01	5.27	7.64	7.82

Table 8. Effect of FPSD on Differential Heart Rate

Source	Sum of Squares	*df*	Mean Square	*F*-statistic	*p*-value
FPSD	261.971	3	87.324	3.68	0.015
Worker	1399.384	5	279.877		
Activity	576.013	3	192.004		
Error	1993.238	84	23.729		
Total	4230.606	95			

The results of the *post-hoc* analysis is shown in Table 9. The results suggest that the use of the RaptorRail resulted in a significantly higher differential heart rate compared to when the CC120 was used. However, the difference between CC120, the ParaClamp, and the MCC130 were not significantly different. Therefore, based on just the differential heartrate, the CC120, the ParaClamp, and the MCC130 is preferable over the RaptorRail.

Table 9. Post-hoc Analysis Results for Differential Heart Rate

FPSD	N	Subset	
		1	2
CC120	24	22.166754	
ParaClamp	24	23.287963	23.287963
MCC130	24	24.262882	24.262882
RaptorRail	24		26.648015
Sig.		0.448	0.087

Postural Assessment

Analysis of the postural data collected using the wearable devices was completed using the mean compound torso angle value for each activity, calculated as the average of all measurements throughout the duration of the individual activities (e.g., install RaptorRail, load CC120).

The descriptive statistics for each of the FPSDs are presented in Table 10 and the ANOVA results are presented in Table 11. As can be seen, the ANOVA results suggests that the postural angle associated with the FPSDs were not equal [F (3,84) = 7.571, $p < 0.01$].

Table 10. Descriptive Statistics for Compound Torso Angle

	FPSD			
	RaptorRail	CC120	MCC130	ParaClamp
Median	36.27	29.60	31.80	32.58
Mean	36.95	29.62	30.58	36.52
Std. Dev	15.40	10.34	9.50	17.46

Table 11. Effect of FPSD on Compound Torso Angle

Source	Sum of Squares	*df*	Mean Square	*F*-statistic	*p*-value
FPSD	1068.371	3	356.124	7.517	<0.01
Worker	3243.691	5	648.738		
Activity	9776.167	3	3258.722		
Error	3979.638	84	47.377		
Total	18067.86	95			

The *post-hoc* results are presented in Table 12. The results revealed significant differences between the RaptorRail–CC120, RaptorRail–MCC130, ParaClamp–CC120, and ParaClamp–MCC130 combinations.

Table 12. Post-hoc Analysis Results for Compound Torso Angle

FPSD	N	Subset	
		1	2
CC120	24	29.6199	
MCC130	24	30.584	
ParaClamp	24		36.5194
RaptorRail	24		36.945
Sig.		0.962	0.996

These results provide sufficient evidence to indicate that, on average, both the CC120 and MCC130 have a lower compound torso angle compared to the RaptorRail and ParaClamp. As a result, workers using the CC120 and MCC130 are more likely to have a more neutral torso posture (i.e., upright stance), reducing the likelihood of developing physical fatigue and WMSD while completing FPSD-related activities.

Average Time per Post

The average time required to complete the various actions for each FPSD was investigated. To obtain the average time, the total activity duration (in seconds) was divided by the number of FPSD posts used during the activity. For example, the average time to install the RaptorRail for Worker # 1 was 154 seconds / 8 posts = 19.25 seconds/post.

The descriptive statistics for each of the FPSDs are presented in Table 13 and the ANOVA results are presented in Table 14. As can be seen, the ANOVA results suggests that the average time to complete the activities for each of the FPSDs were not equal [F (3,84) = 5.738, $p < 0.01$].

Table 13. Descriptive Statistics for the average time per post

	FPSD			
	RaptorRail	CC120	MCC130	ParaClamp
Median	28.11	22.73	25.10	27.10
Mean	29.21	22.90	26.00	26.86
Std. Dev	8.48	7.49	9.11	9.07

Table 14. Effect of FPSD on the Average Time per Post

Source	Sum of Squares	*df*	Mean Square	*F*-statistic	*p*-value
FPSD	490.42	3	163.473	5.738	<0.01
Worker	1655.752	5	331.15		
Activity	2698.465	3	899.488		
Error	2393.116	84	28.489		
Total	7237.754	95			

The *post-hoc* analysis results are presented in Table 15. The results reveal that significant differences exist between the CC120–RaptorRail and CC120–ParaClamp.

Table 15. Post-hoc Analysis Results for the Average Time per Post

FPSD	N	Subset	
		1	2
CC120	24	22.8967	
MCC130	24	25.9985	25.9985
ParaClamp	24	26.8567	26.8567
RaptorRail	24		29.2095
Sig.		0.057	0.167

Based on these results, there is evidence to conclude that the CC120 requires significantly less time for the completion of the multiple activities when compared to the RaptorRail and ParaClamp. Time-efficiency is an indicator of superior productivity. But most importantly, it is also a proxy indicator for safety, as the reduced exposure times may reduce the likelihood of injuries from the completion of the activities. To illustrate, faster installation and dismantling of an FPSD reduces the exposure to the bridge unprotected edge. Similarly, traffic-related hazards are reduced as less time is spent working in close proximity to traffic.

Survey Questionnaire assessing Utility and Usability

The survey questionnaire gathered the respondents' level of agreement with 15 questionnaire items using a scale from (1) for strong disagreement to (7) for strong agreement. The surveys measures the perceived utility and usability from the perspective of the workers. All questions were written in a language such that strong agreement responses (score of 7) were indicative of a more desirable FPSD. The descriptive statistics are presented in Table 16 and the Friedman ANOVA results are presented in Table 17.

Table 16. Descriptive Statistics for Utility and Usability

	FPSD			
	RaptorRail	CC120	MCC130	ParaClamp
Median	4.00	6.30	5.60	6.00
Mean	3.56	6.15	5.34	5.97
Std. Dev.	1.79	0.65	1.20	0.86

Table 17. Effect of FPSD on Utility and Usability

FPSD	Mean Rank	*Chi-Square* statistic	*p*-value
RaptorRail	1	12.268	0.007
CC120	3.33		
MCC130	2.75		
ParaClamp	2.92		

The results suggest that the CC120 is the FPSD with the highest mean rank. In addition, the CC120's low variability compared to the other FPSDs descriptively suggest that most of the study participants provided high-ranking scores (closer to 7) for CC120. In contrast, the RaptorRail had the lowest response mean rank and the highest variability.

The results of the post-hoc analysis is presented in Table 18. As can be seen, the perceived utility and usability for the RaptorRail was significantly lower the other FPSDs (Adjusted *p*-value = 0.01).

Table 18. Pairwise Comparisons of the utility and usability ratings

Pair-wise Comparisons	Std. Test Statistic	Bonferroni Corrected *p*-value
RaptorRail-MCC130	-2.348	0.113
RaptorRail-ParaClamp	-2.571	0.061
RaptorRail-CC120	-3.130	0.010
MCC130-ParaClamp	-0.224	1.000
MCC130-CC120	0.783	1.000
ParaClamp-CC120	0.559	1.000

Summary of Field Testing Results

Based on the differential heart rate, the CC120, the MCC130, and the ParaClamp was preferable over the RaptorRail FPSD. A similar pattern was found for the average time for installment rates. However, when comparing the postural assessment data, the CC120 and MCC130 were statistically superior to the ParaClamp and the Raptor Rail. Finally, when considering utility and usability, the Raptorrail was less superior to the CC120. Therefore, overall, CC120 is the recommended FPSDs based on all the field experiments, however, statistically equivalent performance can be expected from the MCC130.

SAFETY DASHBOARD

To ensure the overall safety of bridge maintenance and inspection workers, this research also developed a decision support system - called the Safety Dashboard. Safety managers and workers will be able to use the Safety Dashboard to obtain customized safety strategies for specific work tasks and bridge characteristics across North Carolina.

A screenshot of the Safety Dashboard input form is presented in Figure 18. The form requires the input of the bridge number in which work is scheduled (item # 1). The form will indicate the user if information for such bridge is in the database. Second, the form requires the user to input the scheduled tasks by selecting the operation, activity, and component using drop-down menus (item # 2). This task input format was obtained from NCHRP Report 668 – Framework for a National Database system for Maintenance Actions on Highway Bridges (Hearn et al. 2010). The record of scheduled activities input by the user will be shown on the form (item # 3). Lastly, the user generates the report (item # 4).

NCHRP Report 668 – Framework for a National Database system for Maintenance Actions on Highway Bridges (Hearn et al. 2010) proposes a "uniform, consistent format and structure for data on bridge maintenance work". To achieve such consistent format, Hearn et al. (2010) used maintenance information from more than 10 federal and state maintenance manuals, resulting in 14 standard bridge components, 8 standards maintenance operations, and several common activities associated with the components and operations.

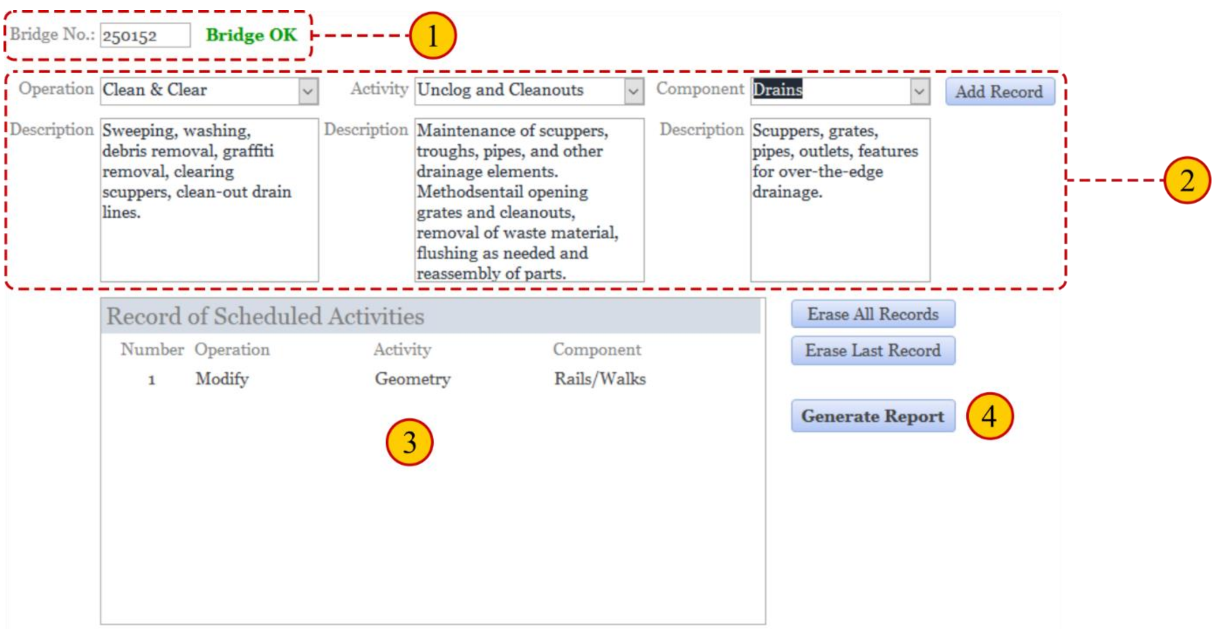


Figure 18. Safety Dashboard Input Form.

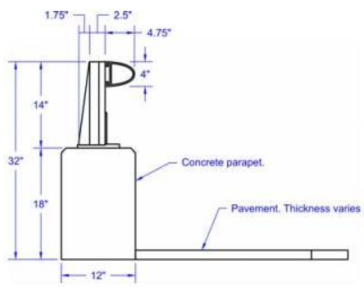
A sample Safety Dashboard report is shown on Figure 19. More specifically, the Safety Dashboard report provides information on the (1) bridge location, (2) guardrail type associated with the bridge, and (3) recommend safe operation procedures (SOP) per NCDOT's Workplace Safety Manual.

Report of Activities and Associated SOPs

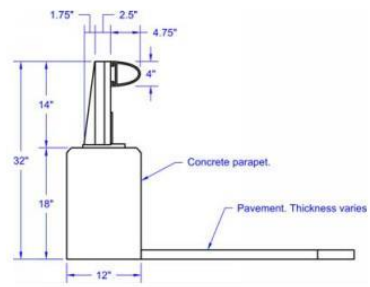
Bridge Details

Bridge No. 250152 **Location:** SR1828 & I95 Location in Google Maps

Left Guardrail Type: 01



Right Guardrail Type: 01



No.	Operation	Activity	Component
1	Clean & Clear	Graffiti	Substructure

Associated SOPs

11A-01	Abrasive and Waterblast Cleaning
11A-23	Metal Cleaning, Chemical/High Pressure Wash
11A-31	Sandblasting
11B-14	Concrete Bridge Super/Sub Structure Maintenance
11B-76	Structural Steel Cleaning
12A-20	Snooper Crane
12A-26	Truck, Aerial Device
12A-37	Work Boat
12A-39	Truck Mounted-Scissors Lift
12A-41	Hydra Platform
12B-21	Power Washer

No.	Operation	Activity	Component
2	Clean & Clear	Unclog and Cleanouts	Drains

Associated SOPs

11B-09	Bridge Deck Cleaning
11E-06	High Pressure Hoses
12A-03	Broom
12A-41	Hydra Platform
12B-13	Hand Tools (Power and Manual)
12B-21	Power Washer

Report generated on 7/25/2018 2:10:31 PM Page 1 of 2

Figure 19. Sample Safety Dasboard Report

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this research was to identify the Fall Protection Supplementary Devices (FPSD) that offered the most benefits to NCDOT and its workforce. This goal was accomplished in three stages. First, a compatibility testing approach using methods of virtual prototyping resulted in the identification of 11 commercially-available FPSDs compatible with over 82% of the bridge guardrails in the state of North Carolina. Second, through a decision-making process, a panel of experts from NCDOT identified desirable characteristics of FPSDs and evaluated the 11 candidate FPSDs to find those that offered the most advantages to reduce safety risk and maximize work efficiency. This process resulted in the acquisition of the two FPSD systems that had the most advantages; that is Fall Protection Guardrail Systems' CC-120 and MCC-130. Third, this study assessed the effects of using four different fall protection devices on the workers' physiological demands, ergonomic risks, productivity, and usability perception using wearable devices and survey questionnaires.

To the knowledge of the authors, this is the first study of its kind and should be of interest to departments of transportation and contractors nationwide. This study makes important contributions to the body of knowledge by 1) increasing the awareness and motivating the adoption of FPSDs to protect the workers against safety hazards during bridge maintenance and inspection operations, 2) identifying FPSDs compatible with more than 22,000 bridge guardrails in the state of North Carolina; especially significant as many of these guardrail designs also present in bridges across the U.S., 3) leveraging innovative technologies such as virtual prototyping and wearable devices that are resource-efficient and cost-effective, 4) providing a framework to solve a nationwide safety issue.

Based on the results of this study, the CC-120 as manufactured by Fall Protection Guardrail Systems, LLC is the FPSD that offers the most benefits for the safety and work efficiency of the workforce. This FPSD is compatible with the 13 most common guardrails evaluated in this study. Based on the desirable characteristics identified by NCDOT's Fall Protection Committee, it offers the most advantages in being easy to install and transport, reducing the exposure of workers to the bridge's unprotected edge, having minimal protruding parts into the work area that can cause struck-by incidents or reduce the available work area, having few movable and removable parts that if lost or broken render the FPSD unusable, and being the most lightweight device.

The advantages of the CC-120 over other FPSDs were corroborated during the field experiments. Consistently, when compared to other FPSDs, the CC-120 required lower levels of physiological exertion, workers were more likely to have upright neutral torso postures, required the least time for the completion of FPSD-related activities (e.g., load onto work truck, install on to guardrail), and was ranked very positively by the workers as being easy to use and effective. Apart from protecting the workers from fall related hazards, the adoption of this FPSD should minimize the physical strain and fatigue, reduce the likelihood of experiencing work-related musculoskeletal disorders (especially to the back), and improve the work efficiency as a result of easy maneuvering and mobilization as well as shorter installation and dismantling periods. All these benefits should improve the motivation of the workers to adopt FPSDs.

An additional quality of the CC-120 praised by the workers and supervisors present during experimental testing was the small footprint of this FPSDs. This was an important characteristic for storage at the yard, but most importantly for transportation of the FPSD due to the limited availability of space in the work vehicles. Currently, work crews must carry many equipment and tools to be able to complete their primary maintenance and inspection tasks. In addition, repair parts and materials must be transported when appropriate. Therefore, a smaller footprint (i.e. less volume) in the work vehicle was said to be very important.

The Fall Protection Guardrail Systems, LLC MCC-130 closely followed the preferred alternative CC-120 in the experiments and provided statistically equivalent performance. Although these two FPSD are very similar in their construction and method of installation, the MCC-130 is 2 lbs. heavier, requires one additional step and two additional parts for adjusting its clamping width, and has a noticeable larger footprint (i.e. volume). These characteristics increased the workers' physical exertion, increased the average time of installation, and negatively affected the workers' perception about this FPSD descriptively (although not statistically different than the CC-120).

Lastly, although BlueWater Manufacturing's ParaClamp was not part of the compatibility and decision-making phases of this study, it was tested during the final stages of this research. This device was praised for its sturdiness and ease of use. More specifically, this FPSD does not require using hand or power tools for installation on to the bridge guardrail. Unfortunately, although easy to use, the data shows that workers are more likely to have higher torso bending angles (bending forward, laterally, or both). In combination with its higher weight (25 lbs.), higher torso bending angles increase the risk of developing musculoskeletal disorders (e.g., back pain).

In summary, the CC-120 provides the most benefits to the health, safety, and productivity of the workforce, followed by the MCC-130, ParaClamp, and GRS-P12. Regardless of which FPSD is chosen by each work group, each FPSD post must be accompanied by at least 3-each 2"x4"x14" lumber blocks to ensure compatibility with all the tested guardrail designs. In some case, these lumber blocs must be placed between the guardrail and the FPSD clamping mechanism to ensure appropriate fit of the FPSD.

IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

As part of the research effort and to foster the implementation of the research findings, FPSDs that enhance safety, productivity, and work-efficiency were identified and were recommended for adoption to NCDOT. Based on this recommendation, NCDOT has already purchased two devices that the workers have already begun using. In addition, utility and usability studies were conducted with the workers after the devices were adopted and implemented in practice.

Apart from this primary implementation effort, a number of additional resources has been shared with NCDOT earlier and is included as part of this report. These resources include:

1) Field Guide booklet: A booklet that includes the design specifications of each of the guardrails that were examined along with the FPSDs that are compatible.
2) FPSD product catalogue: A product catalogue that includes the list of FPSDs that were examined as part of the research study.

3) Safety Dashboard: A decision support system that provides customized safety recommendations for particular work operations on bridges
4) Detailed Compatibility Reference: A detailed reference that presents all the compatibility testing that was conducted as part of the research study.

The resources can be used by supervisors, workers, and mangers for various purposes as indicated below:

- During bridge work planning operations, the supervisors, the managers, and the workers can use the *Field Guide Booklet* to ensure that NCDOT possesses compatible FPSDs to ensure safety and work efficiency.
- The *FPSD product catalogue* can be used by managers and NCDOT decision makers to assist with making purchasing decisions regarding FPSDs.
- The *Safety Dashboard* can be used by supervisors, managers, and workers to safely plan work operations for particular bridge guardrails in North Carolina.
- The *Detailed Compatibility Reference* can be used by managers to examine the installation process of particular FPSDs for specific bridge guardrails.

The use of these resources will be demonstrated during the closeout meeting and with the leadership of the steering committee.

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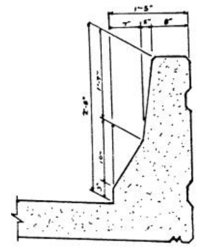
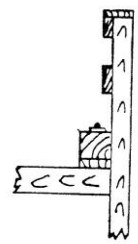
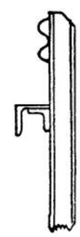
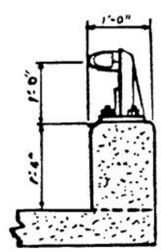
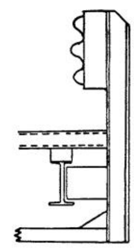
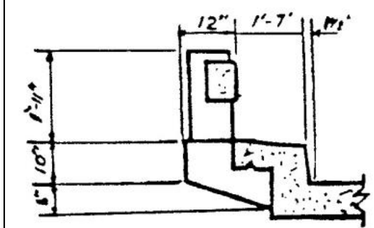
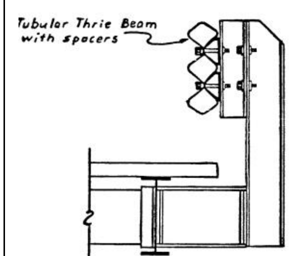
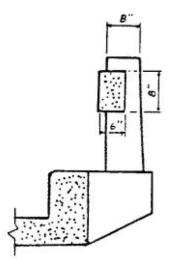
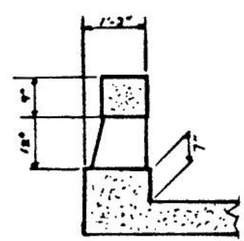
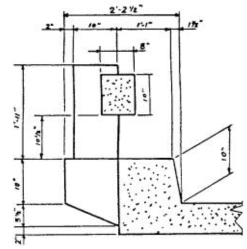
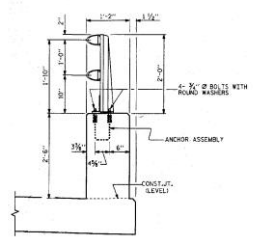
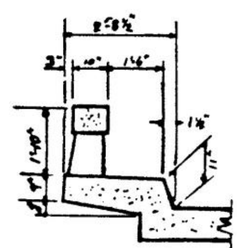
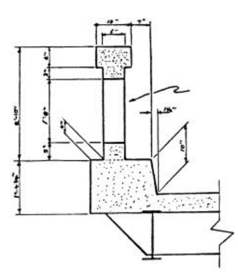
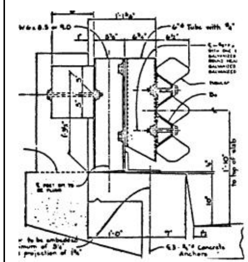
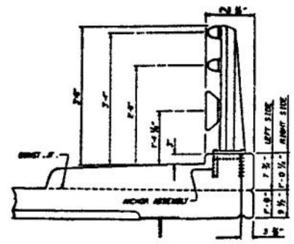
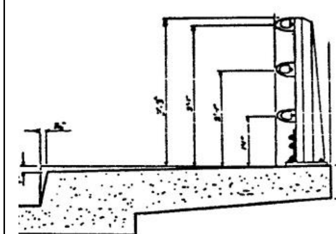
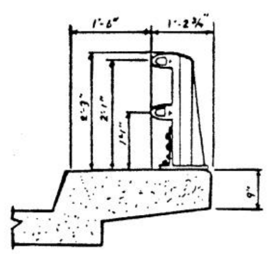
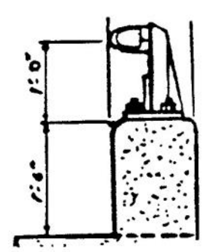
APPENDICES

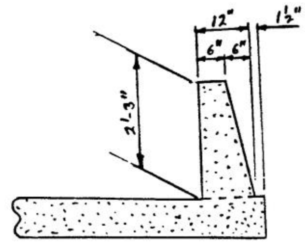
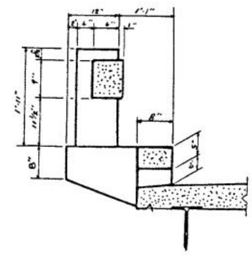
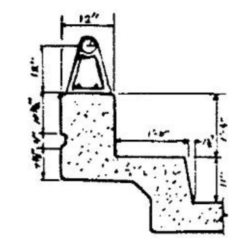
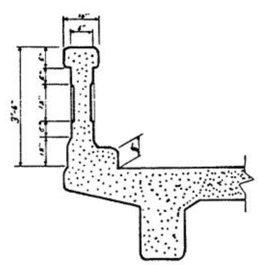
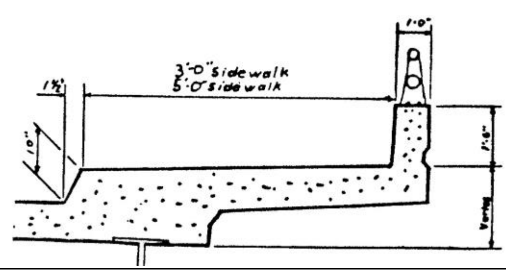
Appendix A – Bridge Guardrails in North Carolina

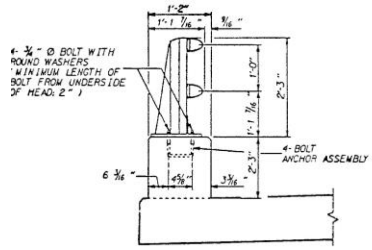
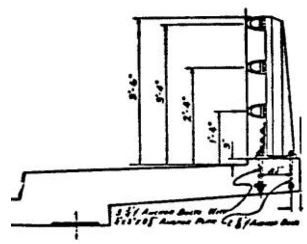
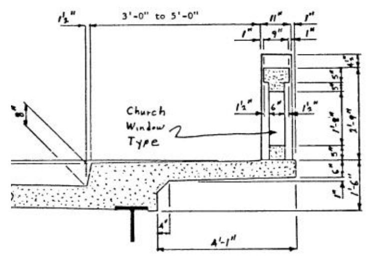
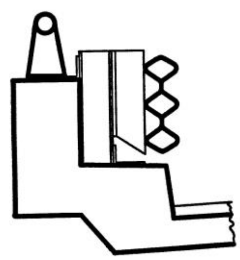
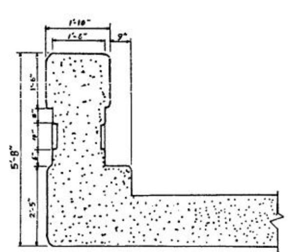
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
04	8306	1	30.7%	No	
22	4961	2	18.4%	No	
23	1909	3	7.1%	No	
99	1168	4	4.3%	N/A	Not available
01	1109	5	4.1%	No	

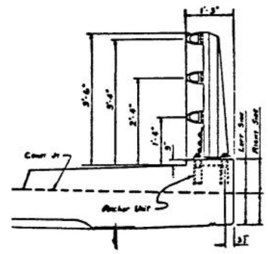
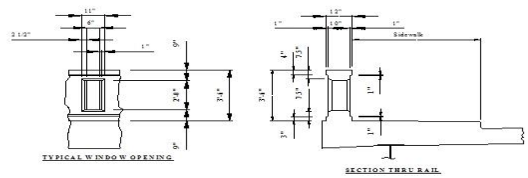
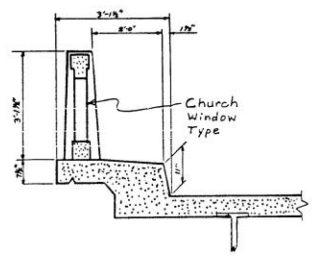
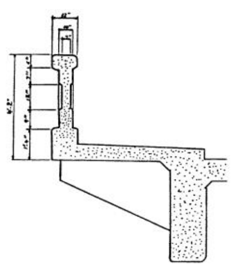
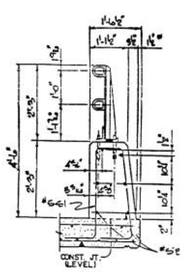
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
25	967	6	3.6%	No	
11	947	7	3.5%	No	
32	826	8	3.1%	No	
24	744	9	2.8%	No	
02	666	10	2.5%	No	

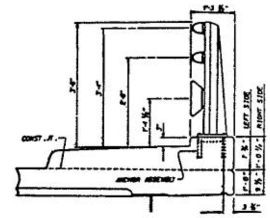
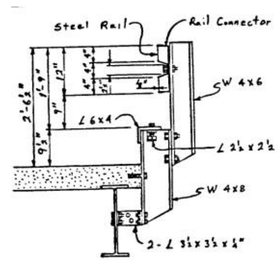
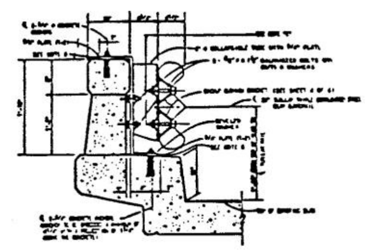
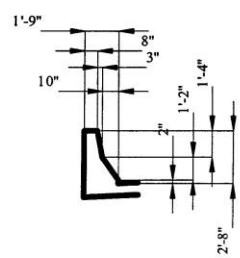
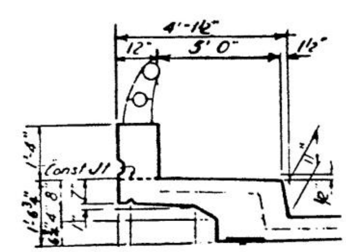
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
14	620	11	2.3%	No	
74	445	12	1.6%	Yes	
00	424	13	1.6%	N/A	00 is used when the bridge has not guardrail
07	423	14	1.6%	No	
31	343	15	1.3%	No	

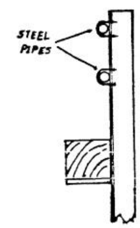
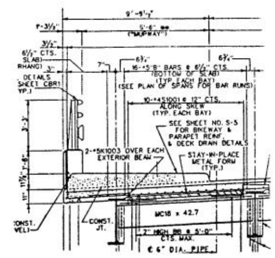
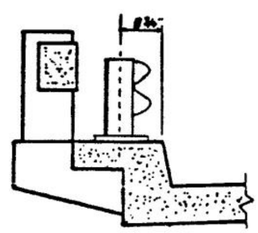
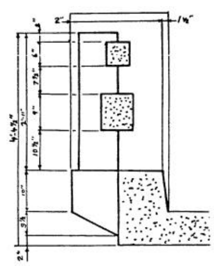
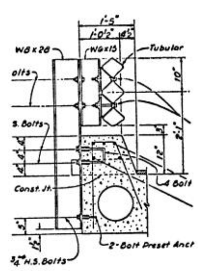
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
33	338	16	1.3%	No	
63	318	17	1.2%	Yes	
03	306	18	1.1%	Yes	
10	235	19	0.9%	No	
62	232	20	0.9%	No	

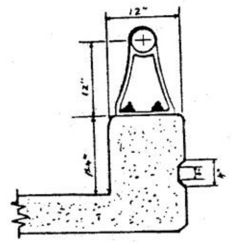
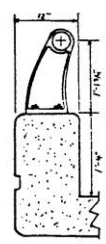
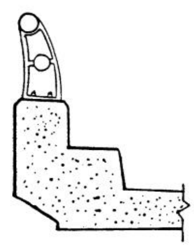
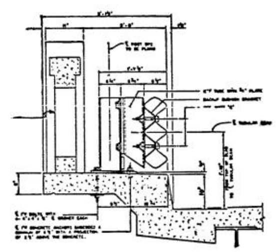
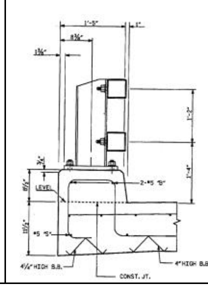
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
39	187	21	0.7%	No	
18	178	22	0.7%	No	
09	161	23	0.6%	No	
30	154	24	0.6%	No	
13	97	25	0.4%	N/A	

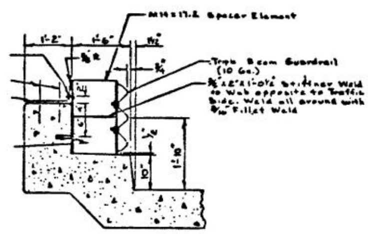
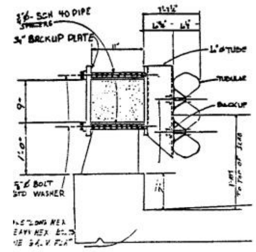
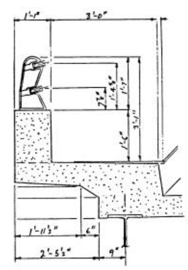
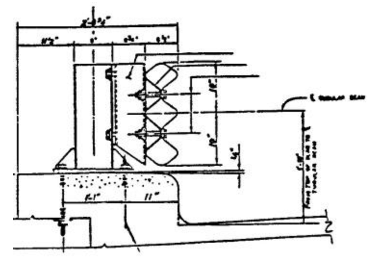
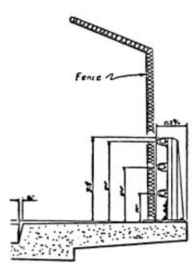
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
70	92	26	0.3%	Yes	
36	61	27	0.2%	Yes	
42	59	28	0.2%	No	
71	54	29	0.2%	N/A	
28	52	30	0.2%	Yes	

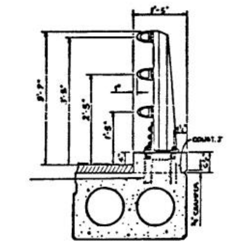
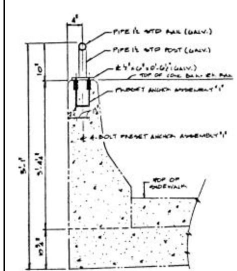
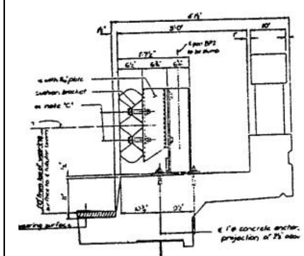
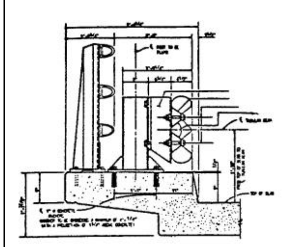
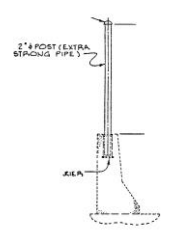
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
37	52	30	0.2%	Yes	
77	49	32	0.2%	Yes	
20	44	33	0.2%	No	
29	42	34	0.2%	Yes	
56	42	34	0.2%	Yes	

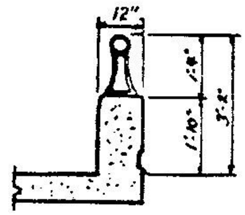
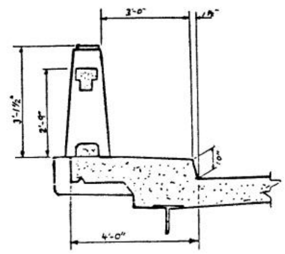
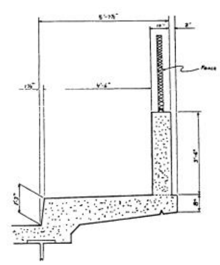
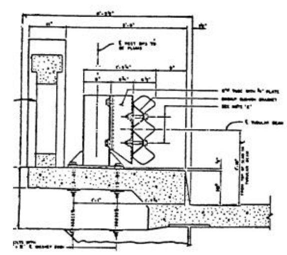
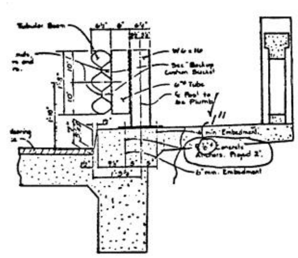
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
60	35	36	0.1%	N/A	
49	32	37	0.1%	No	
52	32	37	0.1%	N/A	
50	28	39	0.1%	N/A	
57	28	39	0.1%	No	

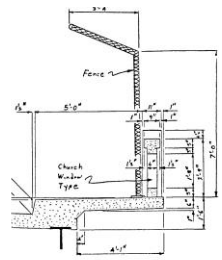
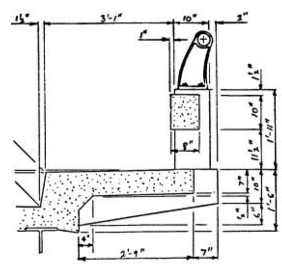
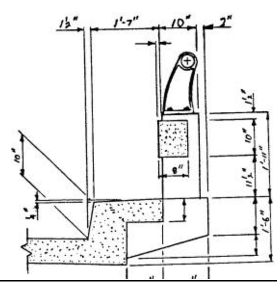
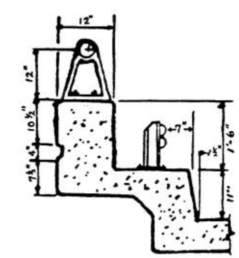
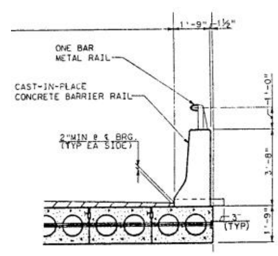
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
26	27	41	0.1%	N/A	
75	25	42	0.1%	Yes	
21	23	43	0.1%	N/A	
15	20	44	0.1%	No	
76	18	45	0.1%	No	

Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
06	16	46	0.1%	No	
05	14	47	0.1%	No	
27	14	47	0.1%	N/A	
34	14	47	0.1%	N/A	
72	13	50	0.0%	No	

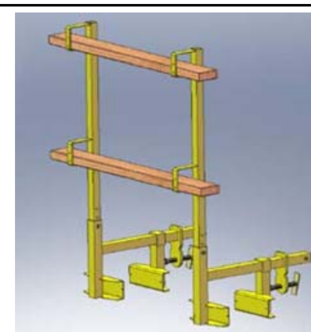
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
40	12	51	0.0%	No	
55	11	52	0.0%	N/A	
48	10	53	0.0%	No	
58	6	54	0.0%	N/A	
44	5	55	0.0%	Yes	

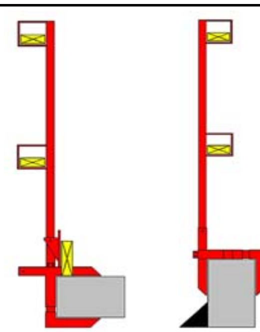
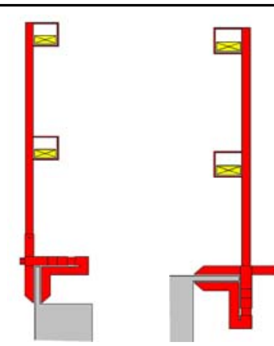
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
38	4	56	0.0%	Yes	
47	4	56	0.0%	Yes	
51	4	56	0.0%	N/A	
53	4	56	0.0%	N/A	 Retrofit Existing Rail Of 2'–0" Sidewalk With Tubular Beam
66	3	60	0.0%	Yes	 Barrier Rail Fence Post

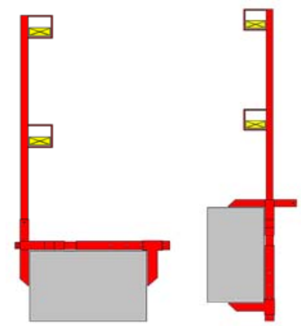
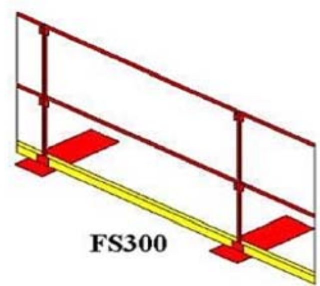
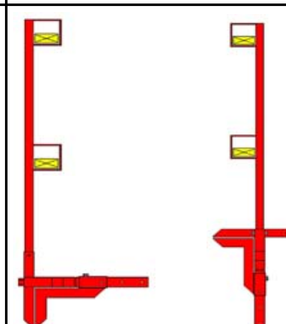
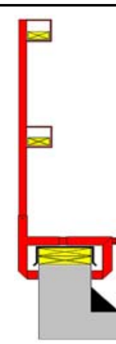
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
08	2	61	0.0%	No	
12	2	61	0.0%	No	
19	2	61	0.0%	Yes	
35	2	61	0.0%	N/A	
41	2	61	0.0%	No	

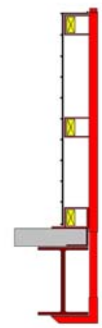
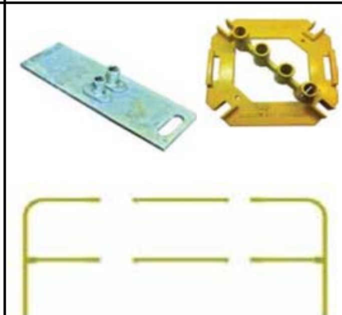
Guardrail Type	Count	Ranking by Count	Percentage of Total Count	Height ≥ 39 inches?	Schematic
43	2	61	0.0%	Yes	
45	2	61	0.0%	Yes	
46	2	61	0.0%	Yes	
59	2	61	0.0%	No	
65	1	70	0.0%	Yes	

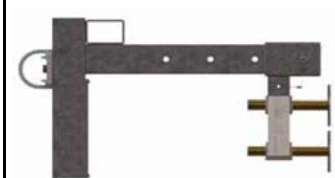
Appendix B – FPSD Product Catalog

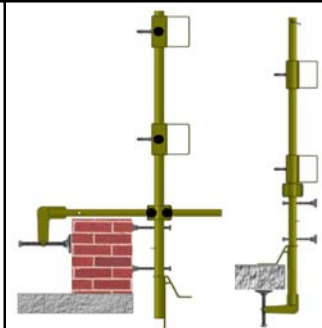
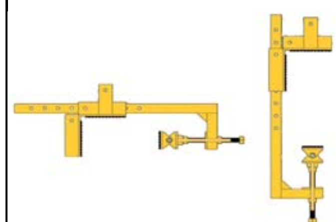
NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES															
			SYSTEM TYPE							TOLER.		REGULATION			
ID	MANUFACTURER	PRODUCT NAME	Guardrail - Parapet clamp	Guardrail - Slab clamp	Guardrail - Freestanding	Guardrail - Beam clamp	Concrete barrier supplement	Parapet - Fall arrest system	Parapet - Fall restraint system	Inst. Tolerance Min [in]	Inst. Tolerance Max [in]	Height Compliance1926.502(b)(1)	Strength Compl 1926.502(b)(3)	ANSI Z359 compliance	
1.1	Blue Water Manufacturing	Safety Rail 2000			X										
1.2	Blue Water Manufacturing	VersaClamp Safety Guardrail	X	X						2	16	X			
1.3	Blue Water Manufacturing	ParaClamp Parapet Guardrail	X							1	25	X			
1.4	Blue Water Manufacturing	MedianClamp Concrete Barrier Protection	X				X			1	25	X			

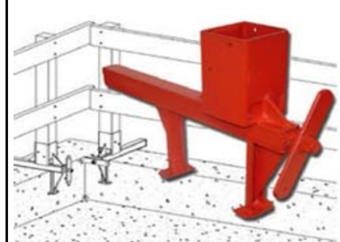
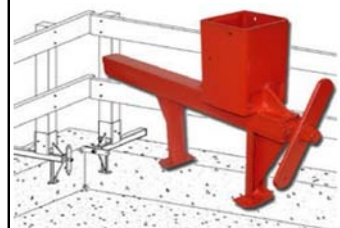
NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES															
			SYSTEM TYPE							TOLER.		REGULATION			
ID	MANUFACTURER	PRODUCT NAME	Guardrail - Parapet clamp	Guardrail - Slab clamp	Guardrail - Freestanding	Guardrail - Beam clamp	Concrete barrier supplement	Parapet - Fall arrest system	Parapet - Fall restraint system	Inst. Tolerance Min [in]	Inst. Tolerance Max [in]	Height Compliance1926.502(b)(1)	Strength Compl 1926.502(b)(3)	ANSI Z359 compliance	
2.1	DBI SALA	Flexiguard Portable Guardrail	X	X						6	24	X			
2.2	DBI SALA	Portable Guardrail System			X							x	x		
3.1	Fall Protection Guardrail Systems, LLC.	C-Clamp - CC120	X	X						7	12	X	X		
3.2	Fall Protection Guardrail Systems, LLC.	C-Clamp 2 - CC125	X	X						0	5	X	X		

NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES															
			SYSTEM TYPE							TOLER.		REGULATION			
ID	MANUFACTURER	PRODUCT NAME	Guardrail - Parapet clamp	Guardrail - Slab clamp	Guardrail - Freestanding	Guardrail - Beam clamp	Concrete barrier supplement	Parapet - Fall arrest system	Parapet - Fall restraint system	Inst. Tolerance Min [in]	Inst. Tolerance Max [in]	Height Compliance1926.502(b)(1)	Strength Compl 1926.502(b)(3)	ANSI Z359 compliance	
3.3	Fall Protection Guardrail Systems, LLC.	Master C-Clamp - MCC130	X	X							48	X	X		
3.4	Fall Protection Guardrail Systems, LLC.	The Free Standing system - FS300			X										
3.5	Fall Protection Guardrail Systems, LLC.	The Prime C-Clamp - PCC135	X	X						0	8				
3.6	Fall Protection Guardrail Systems, LLC.	The Para-Clamp - PCC125	X									X	X		

NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES																
			SYSTEM TYPE							TOLER.		REGULATION			
ID	MANUFACTURER	PRODUCT NAME	Guardrail - Parapet clamp	Guardrail - Slab clamp	Guardrail - Freestanding	Guardrail - Beam clamp	Concrete barrier supplement	Parapet - Fall arrest system	Parapet - Fall restraint system	Inst. Tolerance Min [in]	Inst. Tolerance Max [in]	Height Compliance1926.502(b)(1)	Strength Compl 1926.502(b)(3)	ANSI Z359 compliance	
3.7	Fall Protection Guardrail Systems, LLC.	The Slab Master - SMS100		X											
4.1	Guardian Fall Protection	G-Rail			X							X	X		
4.2	Guardian Fall Protection	OMG Rail			X							X	X		
4.3	Guardian Fall Protection	Alligator Parapet Guardrail system	X							2	16	X	X		

NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES															
			SYSTEM TYPE							TOLER.		REGULATION			
ID	MANUFACTURER	PRODUCT NAME	Guardrail - Parapet clamp	Guardrail - Slab clamp	Guardrail - Freestanding	Guardrail - Beam clamp	Concrete barrier supplement	Parapet - Fall arrest system	Parapet - Fall restraint system	Inst. Tolerance Min [in]	Inst. Tolerance Max [in]	Height Compliance1926.502(b)(1)	Strength Compl 1926.502(b)(3)	ANSI Z359 compliance	
4.4	Guardian Fall Protection	Parapet Clamp Guardrail System	X							4	24	X	X		
4.5	Guardian Fall Protection	Parapet Anchor	X					X	X	4	20	X	X	X	
4.6	Guardian Fall Protection	C-Slab Grabber		X						1.5	36	X	X		
5.1	AES Raptor	RaptorRail	X							3	24	X	X		

NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES															
			SYSTEM TYPE							TOLER.		REGULATION			
ID	**MANUFACTURER**	**PRODUCT NAME**	**Guardrail - Parapet clamp**	**Guardrail - Slab clamp**	**Guardrail - Freestanding**	**Guardrail - Beam clamp**	**Concrete barrier supplement**	**Parapet - Fall arrest system**	**Parapet - Fall restraint system**	**Inst. Tolerance Min [in]**	**Inst. Tolerance Max [in]**	**Height Compliance1926.502(b)(1)**	**Strength Compl 1926.502(b)(3)**	**ANSI Z359 compliance**	
5.2	AES Raptor	All-In-One	X	X							24	X	X		
5.3	AES Raptor	Universal Guardrail Parapet Clamp	X	X						3	24				
6.1	Kee Safety	KeeGuard			X							X	X		
7.1	FallTech	Parapet Wall Anchor - 7406A						X	X	0.5	15			X	

NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES															
			SYSTEM TYPE							TOLER.		REGULATION			
ID	MANUFACTURER	PRODUCT NAME	Guardrail - Parapet clamp	Guardrail - Slab clamp	Guardrail - Freestanding	Guardrail - Beam clamp	Concrete barrier supplement	Parapet - Fall arrest system	Parapet - Fall restraint system	Inst. Tolerance Min [in]	Inst. Tolerance Max [in]	Height Compliance1926.502(b)(1)	Strength Compl 1926.502(b)(3)	ANSI Z359 compliance	
8.1	Ellis Manufacturing	Parapet Guardrails GRS-P12	X							4	12	X	X		
8.2	Ellis Manufacturing	Parapet Guardrails GRS-P24	X							4	24	X	X		
8.3	Ellis Manufacturing	QuickRail Parapet Guardrail QR-P12	X							4	12				
8.4	Ellis Manufacturing	QuickRail Parapet Guardrail QR-P24	X							4	24				

NCDOT - FALL PROTECTION SUPPLEMENTARY DEVICES															
			SYSTEM TYPE							TOLER.		REGULATION			
ID	MANUFACTURER	PRODUCT NAME	Guardrail - Parapet clamp	Guardrail - Slab clamp	Guardrail - Freestanding	Guardrail - Beam clamp	Concrete barrier supplement	Parapet - Fall arrest system	Parapet - Fall restraint system	Inst. Tolerance Min [in]	Inst. Tolerance Max [in]	Height Compliance1926.502(b)(1)	Strength Compl 1926.502(b)(3)	ANSI Z359 compliance	
8.5	Ellis Manufacturing	Slab Grabber / guardrail stanchion GSR-1		X						4	36	X	X		
9.1	Latchways Fall Protection	Versi-Rail			X										

Appendix C – Detailed Compatibility Reference

COMPATIBILITY TESTING OF SUPPLEMENTAL FALL PROTECTION DEVICES ON NCDOT BRIDGES

Detailed Compatibility Reference

Research Institution:
North Carolina State University

NC STATE UNIVERSITY

Sponsoring Organization:
North Carolina Department of Transportation

NCDOT

TABLE OF CONTENTS

1. INTRODUCTION

This document presents the preliminary results of the compatibility testing between various guardrail types across the State of North Carolina and Fall Protection Supplementary Devices (FPSD). This research effort includes an industry survey to identify promising and efficient FPSD systems available in the market, the identification and extraction of design features, and 3D modeling to test compatibility with guardrails.

To accomplish the objectives of this research, the most common type of bridge guardrails in the State of North Carolina were first identified. This was followed by the extraction of design features from the NCDOT Wiggins database to develop 3D models of the bridge rails. Whenever necessary, additional information was obtained from the Federal Highway Administration for accurate modeling. The guardrail types modeled, the quantity of each type across the state, and the percentage of the total bridge guardrails across the state are shown in Table 1.

Simultaneously, as the 3D models for the guardrail were being developed, data relevant to the FPSDs were gathered. FPSD are systems that can be temporarily installed over bridge guardrails while work is being performed on the bridge. The objective is to increase the height of the guardrail to an OSHA compliant height of 42” (± 3 inches). Promising FPSD systems were identified through a market research by contacting suppliers of safety products and nationally recognized safety associations and manufacturers. After the FPSD systems were identified, the manufacturers were contacted and detailed information of the products (i.e. CAD drawings or 3D models) to create the 3D models was requested. The developed 3D models were then used to test product assembly and perform joint and motion studies. Unfortunately, not all manufacturers provided us the requested information. Therefore, some products that were promising were excluded from the analysis.

Table 1 - Bridge guardrail types included in the compatibility studies.

Guardrail Type	Description	Quantity (each)	Percentage of total
04	Jersey Barrier	8,306	30.73%
22	Wood Guardrail	4,961	18.35%
23	Steel W-Beam	1,909	7.06%
01	Aluminum 1-Bar	1,109	4.10%
25	Thrie-Beam	967	3.58%
11	Concrete 1-Bar Middle	947	3.50%
32	Tubular Thrie-Beam	826	3.06%
24	Concrete 1-Bar Middle	744	2.75%
02	Concrete 1-Bar Top	666	2.46%
14	Concrete 1-Bar Middle	620	2.29%
07	Concrete 1-Bar Top	423	1.56%
31	Concrete Church Window	343	1.27%
33	Retrofit – Tubular Thrie-Beam	338	1.25%
	TOTALS	**22,159**	**81.96%**

What follows is an in-depth analysis of the fit of the identified FPSDs for each of the bridge guardrail described in Table 1. The process of testing for compatibility in a virtual environment was very effective in many ways. First, we did not have to purchase, rent, or borrow any of the devices; minimizing the cost for the project. Second, the setup of multiple bridge work zones was avoided. This is a time and resource consuming activity that exposes workers, researchers and drivers to dangerous hazards. Lastly, we have the ability to rapidly analyze and generate compatibility alternatives on-demand, with the ability to generate visual products such as photo-realistic renderings or animations.

The following are important notes before reading this report:

1. 3D models of guardrails and FPSD were created using Autodesk® Fusion 360™.
2. The dimension tolerance between actual guardrails and the 3D models is approximately 1”. This was validated by measuring one representative bridge guardrail of each of the guardrail types in Table 1.
3. The principal objective of this report is to assess the compatibility of FPSD and the bridge guardrails described in Table 1. Engineering judgment of the researchers was used to determine the proposed fit for each FPSDs on each guardrail. No structural analysis has been performed to the FPSDs or bridge guardrails to verify that they can withstand the forces specified by OSHA in 29 CFR 1926.502(b)(3) and 29 CFR 1926.502(b)(5).
4. The intrusion into the work area for each FPSD was measured from the innermost part of the guardrail, meaning the face closest to the centerline of the bridge when observed from the top. For details, see dimension “A” on Figure 1 and Figure 2.

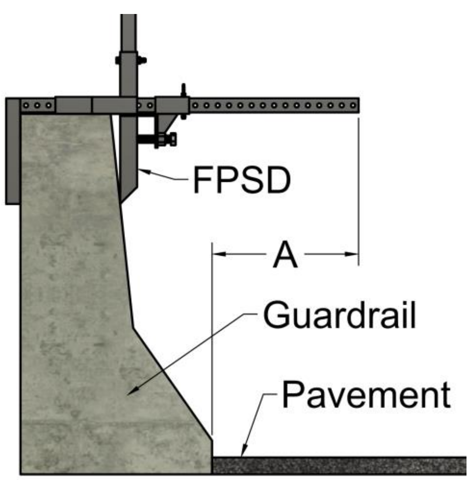


Figure 1 - Intrusion measurement. Section

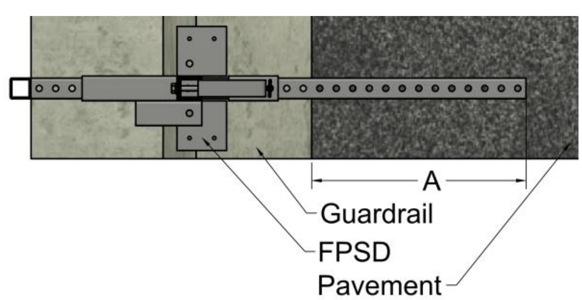


Figure 2 - Intrusion measurement. Top view

5. For reference, the height of the worker depicted in all renderings is 72” (6 feet).
6. Due to the irregular shape of some guardrails, or to the clamping limitations for some FPSD, in some cases, additional items may be needed to secure the FPSDs. During a site visit performed by the researchers, it was observed that NCDOT workers use wood blocks for this purpose. Therefore, in this report, we assume that wood blocks can be

used when necessary. Because in most cases, the guardrail width is lesser than the minimum clamping distance of the FPSD, the compatibility charts report the minimum width (W) and length (L) of the wood block. Depth (D) is not a concern and will not be reported. If wider or longer wood blocks are available, these can be used unless otherwise noted. For example, 2”W, 4”D, and 12”L are shown in Figure 3 and Figure 4. In this case, 4” W, 6” D, 16” L will also work. However, no smaller blocks than specified can be used. Please note that the dimensions specified in the report are nominal sizes for dimensional lumber. Yet, the modeling of the wood blocks has been done with Standard Dressed Size as specified in Table 1B of the National Design Specification Supplement for Wood Construction, 2015 edition.

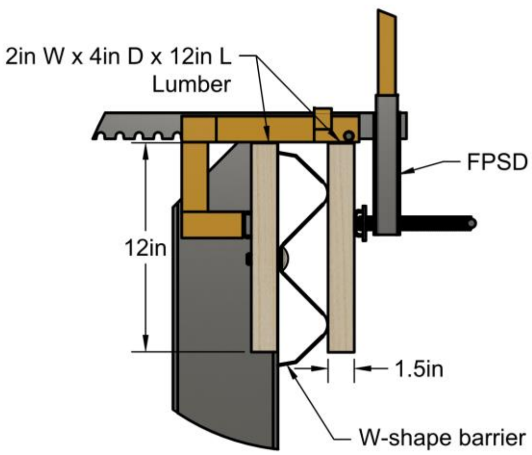


Figure 3 - Guardrail fit with wood blocks. Section

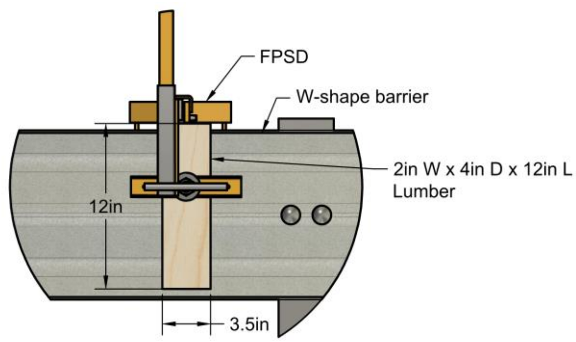


Figure 4 - Guardrail fit with wood blocks. Front view

7. The FPSDs evaluated for this report are presented in Section 2. When two products of similar design were compatible with a specific bridge railing (e.g., ID 8.1 and 8.2) only one of the two is depicted in the renderings (e.g., ID 8.1). By not placing both products in the rendering, we were able to reduce the clutter in the images. However, the ID for both products is noted in the renderings.

8. Although some renderings depict many products, detailed information is only provided for those FPSD that were compatible with the 13 guardrail types presented in this report. In other words, if one FPSD is not compatible with all guardrail types in this report, the compatibility information is not provided.

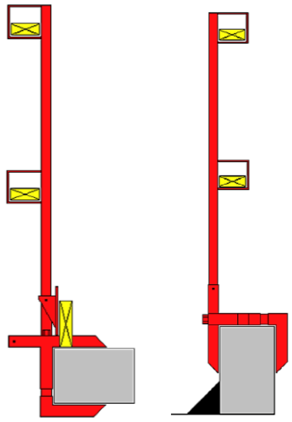
2. FALL PROTECTION SUPPLEMENTARY DEVICES (FPSD)

This section provides information regarding the 11 FPSDs that were compatible with the 13 guardrail types presented in this report.

ID No.: 2.1
Manufacturer: DBI Sala
Product Name: Flexiguard Portable Guardrail

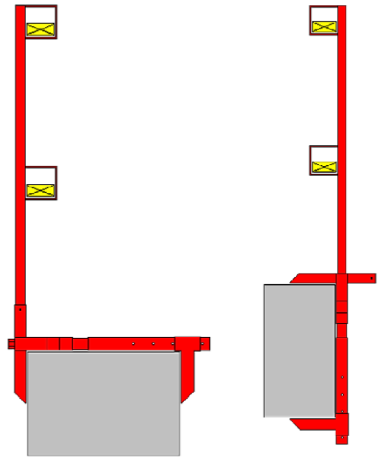
Weight: 18 lbs.
Railings: 2”x4” lumber.
Clamp Range: 6” to 24”.
Usage: Slab clamp; Parapet clamp.

ID No.: 3.1
Manufacturer: Fall Protection Guardrail Systems
Product Name: C-Clamp CC120



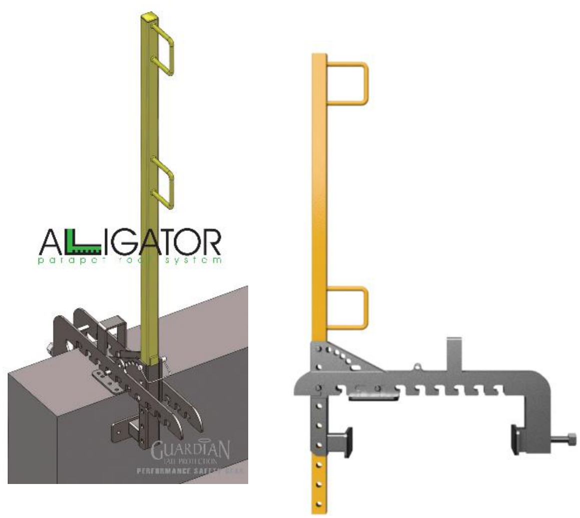
Weight: 13 lbs.
Railings: 2”x4” lumber.
Clamp Range: 7” to 12”.
Usage: Slab clamp; Parapet clamp.

ID No.: 3.3
Manufacturer: Fall Protection Guardrail Systems
Product Name: C-Clamp MCC130



Weight: 15 lbs.
Railings: 2”x4” lumber.
Clamp Range: 8” to 48”.
Usage: Slab clamp; Parapet clamp.

ID No.: 4.3
Manufacturer: Guardian Fall Protection
Product Name: Alligator Parapet Guardrail Systems

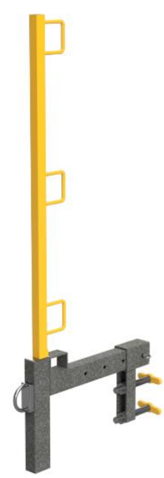


Weight: 42 lbs.
Railings: 2”x4” lumber.
Clamp Range: 2” to 16”.
Usage: Parapet clamp.

ID No.: 4.4
Manufacturer: Guardian Fall Protection
Product Name: Parapet Clamp Guardrail System

Weight: 38 lbs.
Railings: 2”x4” lumber.
Clamp Range: 4” to 16”.
Usage: Parapet clamp.

ID No.: 4.5
Manufacturer: Guardian Fall Protection
Product Name: Parapet Anchor

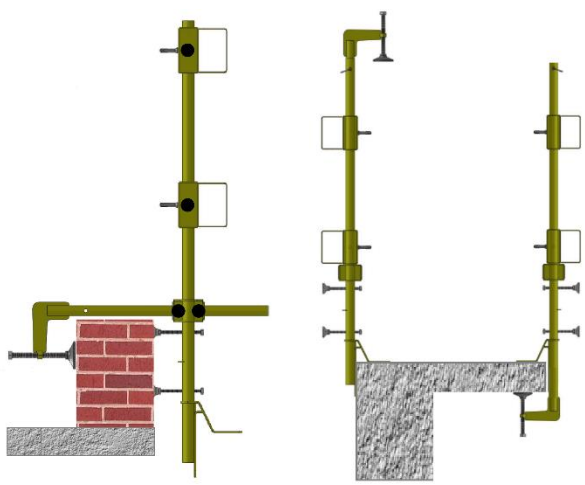


Weight: 33 lbs.
Railings: 2”x4” lumber.
Clamp Range: 4” to 20”.
Usage: Parapet clamp; Anchor for personal fall arrest & restraint systems

ID No.:	5.1
Manufacturer:	AES Raptor
Product Name:	RaptorRail


Weight:	37 lbs.
Railings:	Proprietary, metallic.
Clamp Range:	3” to 24”.
Usage:	Parapet clamp.

ID No.:	5.2
Manufacturer:	AES Raptor
Product Name:	All-in-One



Weight:	25 lbs.
Railings:	Proprietary, metallic.
Clamp Range:	0” to 24”.
Usage:	Slab Clamp; Parapet clamp.

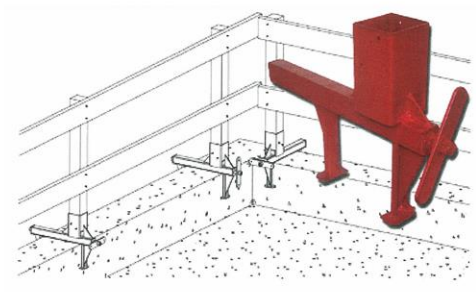
ID No.: 5.3
Manufacturer: AES Raptor
Product Name: Universal Guardrail Parapet Clamp

Weight: 37 lbs.
Railings: Proprietary, metallic.
Clamp Range: 3” to 24”.
Usage: Slab Clamp; Parapet clamp.

ID No.: 8.1 / 8.2
Manufacturer: Ellis Manufacturing
Product Name: Parapet Guardrail GRS-P12 / GRS-P24

Weight: 25 lbs.
Railings: 2”x4” lumber.
Clamp Range: 4” to 12” / 4” to 24”.
Usage: Parapet clamp.

ID No.: 8.3 / 8.4
Manufacturer: Ellis Manufacturing
Product Name: QuickRail Parapet Guardrail QR-P12 / QR-P24



Weight: 19 lbs. including 4”x4” lumber post.
Railings: 2”x4” lumber.
Clamp Range: 4” to 12” / 4” to 24”
Usage: Parapet clamp.

3. GUARDRAIL TYPE 01 – 1-Bar Aluminum

3.1 Description

18” high, 12” wide concrete parapet with 4.75” x 4” semi-elliptical 1-bar aluminum rail 12” over the concrete parapet. The aluminum bar is supported by steel posts. The guardrail height above working surface is approximately 32”. A section of this guardrail is shown in Figure 5.

We considered two fitting options for this guardrail. First, fitting the FPSD over the 12” wide concrete parapet and under the aluminum bar. Second, fitting the FPSD over the aluminum rail. Because of the square shape and sturdiness of the concrete parapet, when an FPSD fitted over the parapet, it was not tested over the aluminum bar.

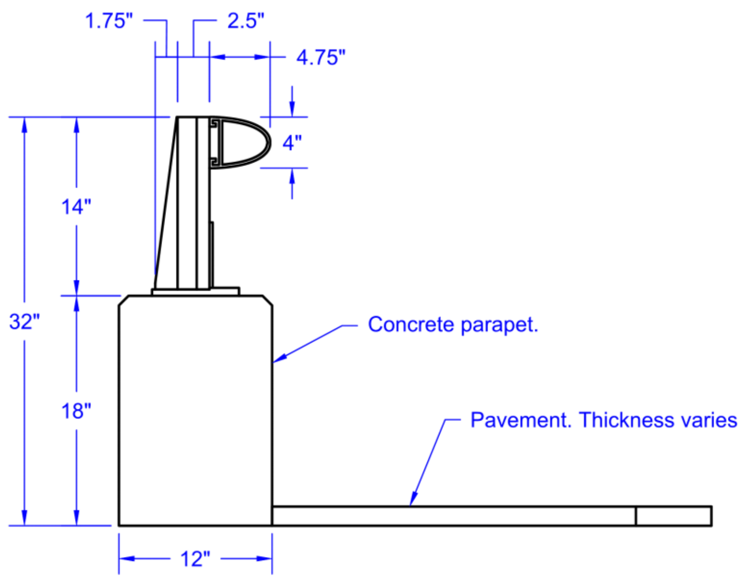


Figure 5 – Guardrail Type 01 section

3.2 Compatibility Chart

Table 2 – Compatibility chart for Guardrail Type 01

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	**Parapet:** The device fits over the concrete parapet. Intrusion into the work area is approximately 18”. **Guardrail:** Because the device fits over the parapet, it was not tested over the guardrail.
3.1	C-Clamp - CC120	**Parapet:** The device maximum opening is 12”. Therefore, this device may fit in the concrete parapet. However, because construction tolerances can vary widely, the devices has been deemed to be **not compatible** with the parapet as there is a high probability of the device not fitting the parapet if 12” width is exceeded. **Guardrail:** This device fits over the semi-elliptical aluminum bar. One 2”W x 12”L lumber piece in the back of the bar, and one 2W x 18L lumber piece in the front of the bar are need to ensure proper fit. Intrusion into the work area is approximately 4”.
3.3	Master C-Clamp - MCC130	**Parapet:** This device fits the concrete parapet. Intrusion into the work area is approximately 2.25”.

ID	PRODUCT NAME	COMPATIBILITY NOTES
		Guardrail: The device was not tested for fit over the aluminum bar because the parapet fit is firmer.
4.3	Alligator Parapet Guardrail system - 15167	**Parapet:** This device fits over the concrete parapet. Intrusion into the work area is approximately 6.5”. **Guardrail:** The device was not tested for fit over the aluminum bar.
4.4	Parapet Clamp Guardrail System - 15170	**Parapet:** This device fits over the concrete parapet. Intrusion into the work area is approximately 7”. **Guardrail:** The device was not tested for fit over the aluminum bar.
4.5	Parapet Anchor - 15171	**Parapet:** This device fits over the concrete parapet. Intrusion into the work area is approximately 9”. **Guardrail:** The device was not tested for fit over the aluminum bar.
5.1	RaptorRail	**Parapet:** This device fits over the concrete parapet. Intrusion into the work area is approximately 8.75”. **Guardrail:** The device was not tested for fit over the aluminum bar.
5.2	All-In-One	**Parapet:** This device fits over the concrete parapet. Intrusion into the work area is approximately 8.75”. **Guardrail:** The device was not tested for fit over the aluminum bar.
5.3	Universal Guardrail Parapet Clamp	**Parapet:** This device fits over the concrete parapet. Intrusion into the work area is approximately 8.75”. **Guardrail:** The device was not tested for fit over the aluminum bar.
8.1	Parapet Guardrails GRS-P12	**Parapet:** This device **does not fit** over the parapet. The aluminum bar interferes with the post. **Guardrail.** The device fits over the semi-elliptical aluminum bar. One 2”W x 18”L lumber piece in the front of the bar is needed to ensure proper fit and transferring of forces to the guardrail assembly. Intrusion into the work area is approximately 4.25”.
8.2	Parapet Guardrails GRS-P24	**Parapet:** This device **does not fit** over the parapet. The aluminum bar interferes with the post. **Guardrail.** The device fits over the semi-elliptical aluminum bar. One 2”W x 18”L lumber piece in the front of the bar is needed to ensure proper fit and transferring of forces to the guardrail assembly. Intrusion into the work area is approximately 4.25”.
8.3	QuickRail Parapet Guardrail QR-P12	**Parapet:** This device **does not fit** over the parapet. The aluminum bar interferes with the 4x4 wooden post. **Guardrail:** The device fits over the semi-elliptical aluminum bar. One 2”W x 18”L lumber piece in the front of the bar is needed to ensure proper fit and transferring of forces to the guardrail assembly. Intrusion into the work area is approximately 4.5”.
8.4	QuickRail Parapet Guardrail QR-P24	**Parapet:** This device **does not fit** over the parapet. The aluminum bar interferes with the 4x4 wooden post. **Guardrail:** The device fits over the semi-elliptical aluminum bar. One 2”W x 18”L lumber piece in the front of the bar is needed to ensure proper fit and transferring of forces to the guardrail assembly. Intrusion into the work area is approximately 4.5”.

3.3 Renderings

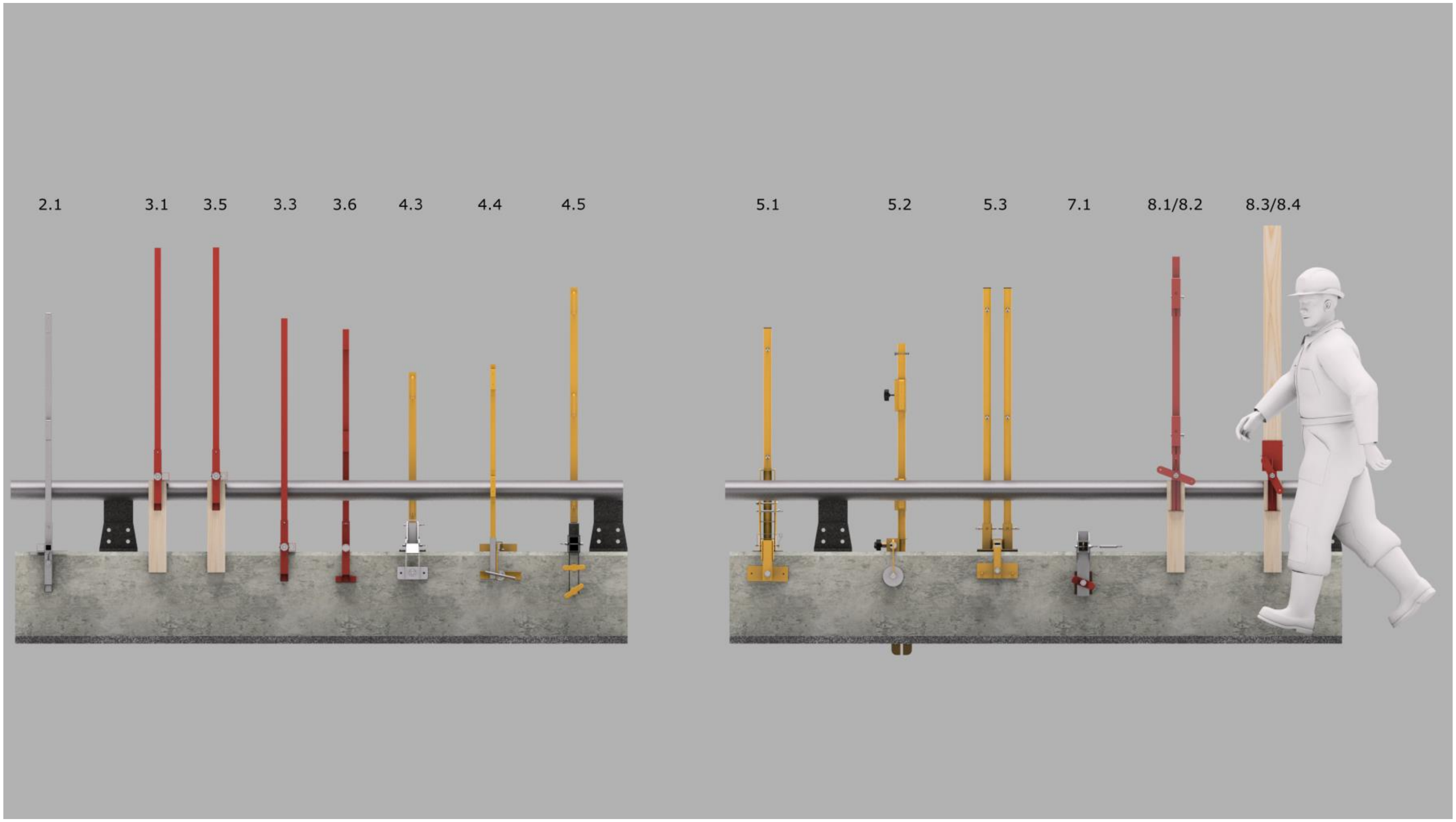


Figure 6 – Guardrail Type 01; view from the east

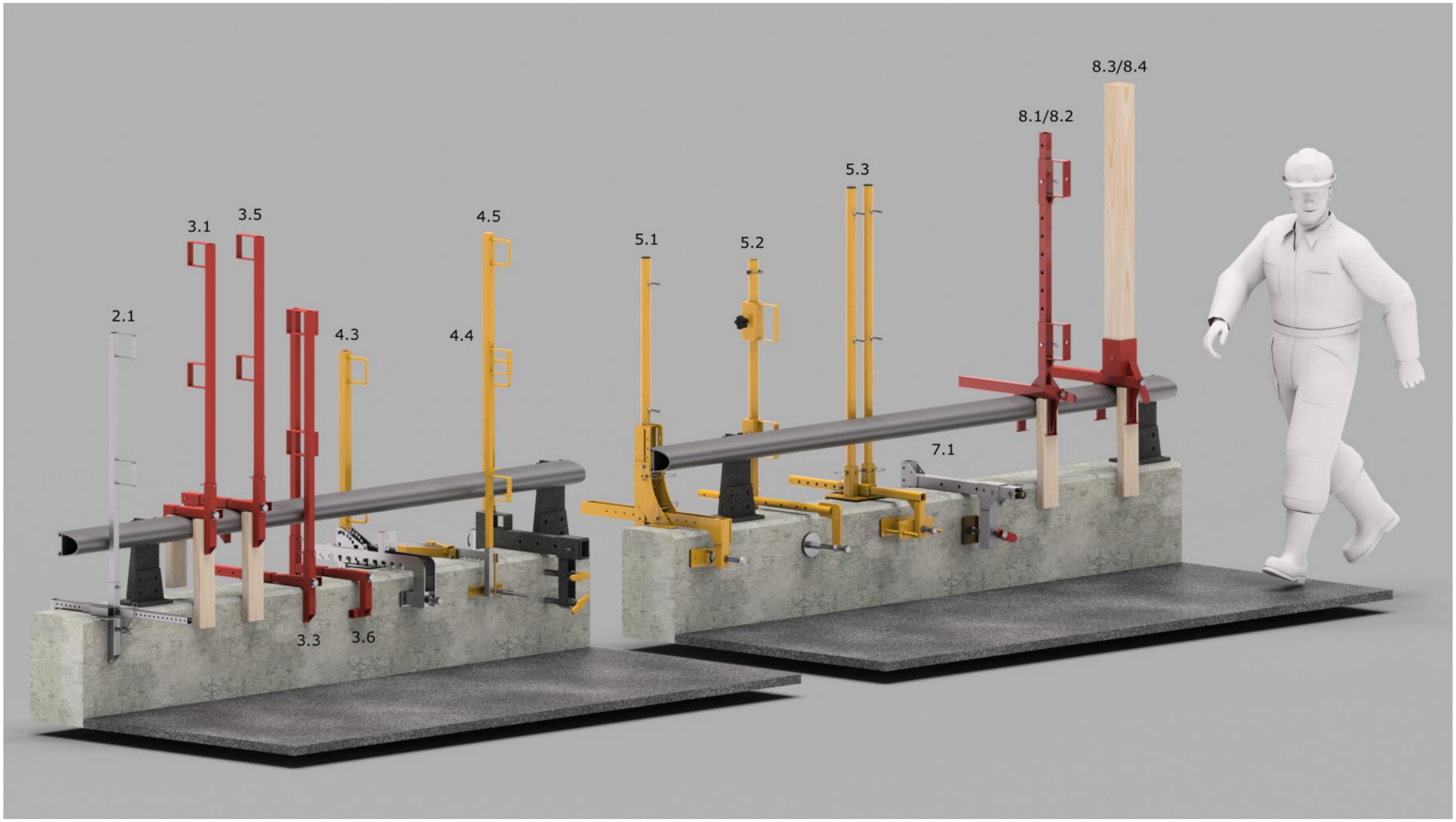


Figure 7 – Guardrail Type 01; view from the southeast

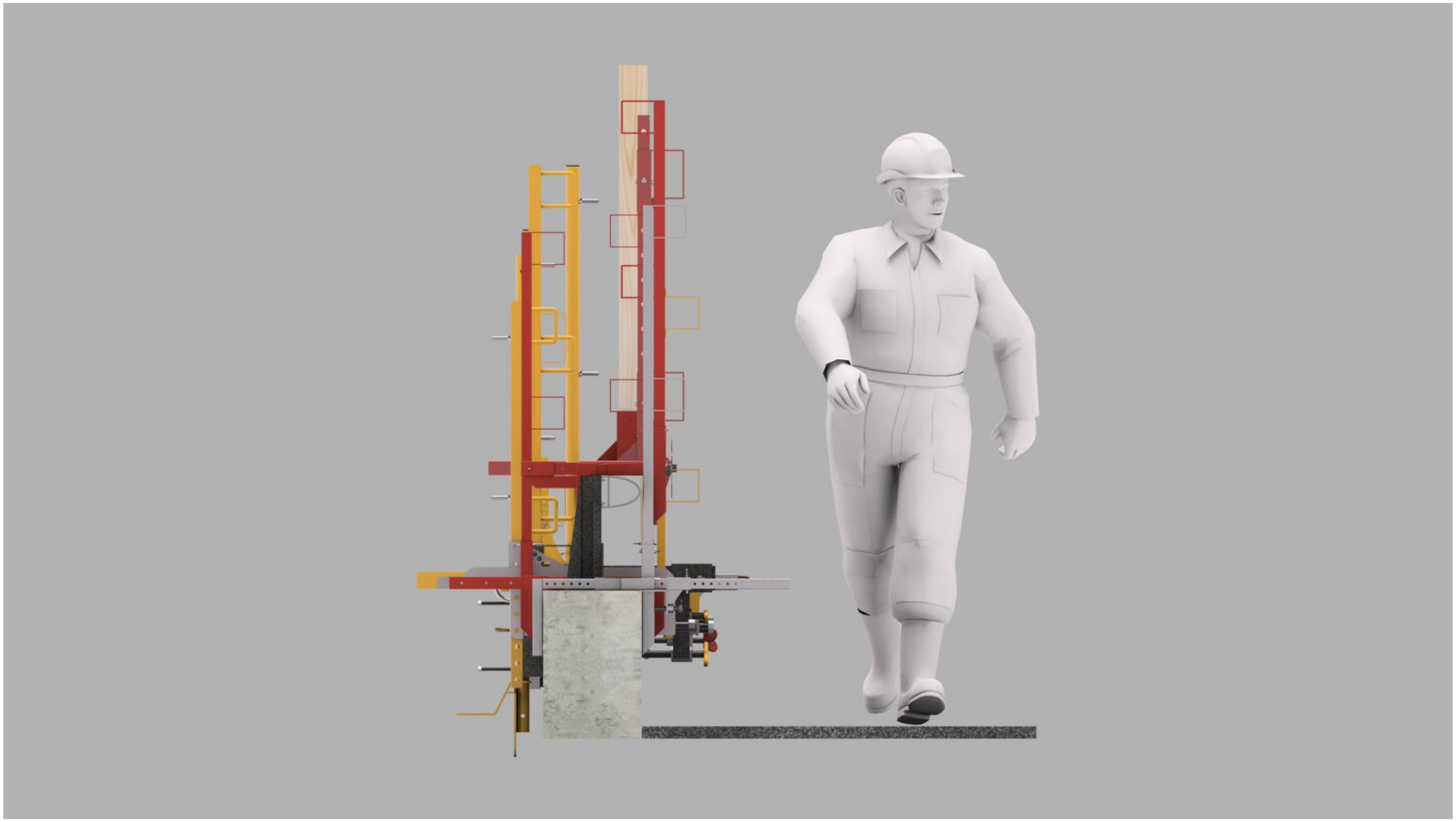


Figure 8 – Guardrail Type 01; view from the south

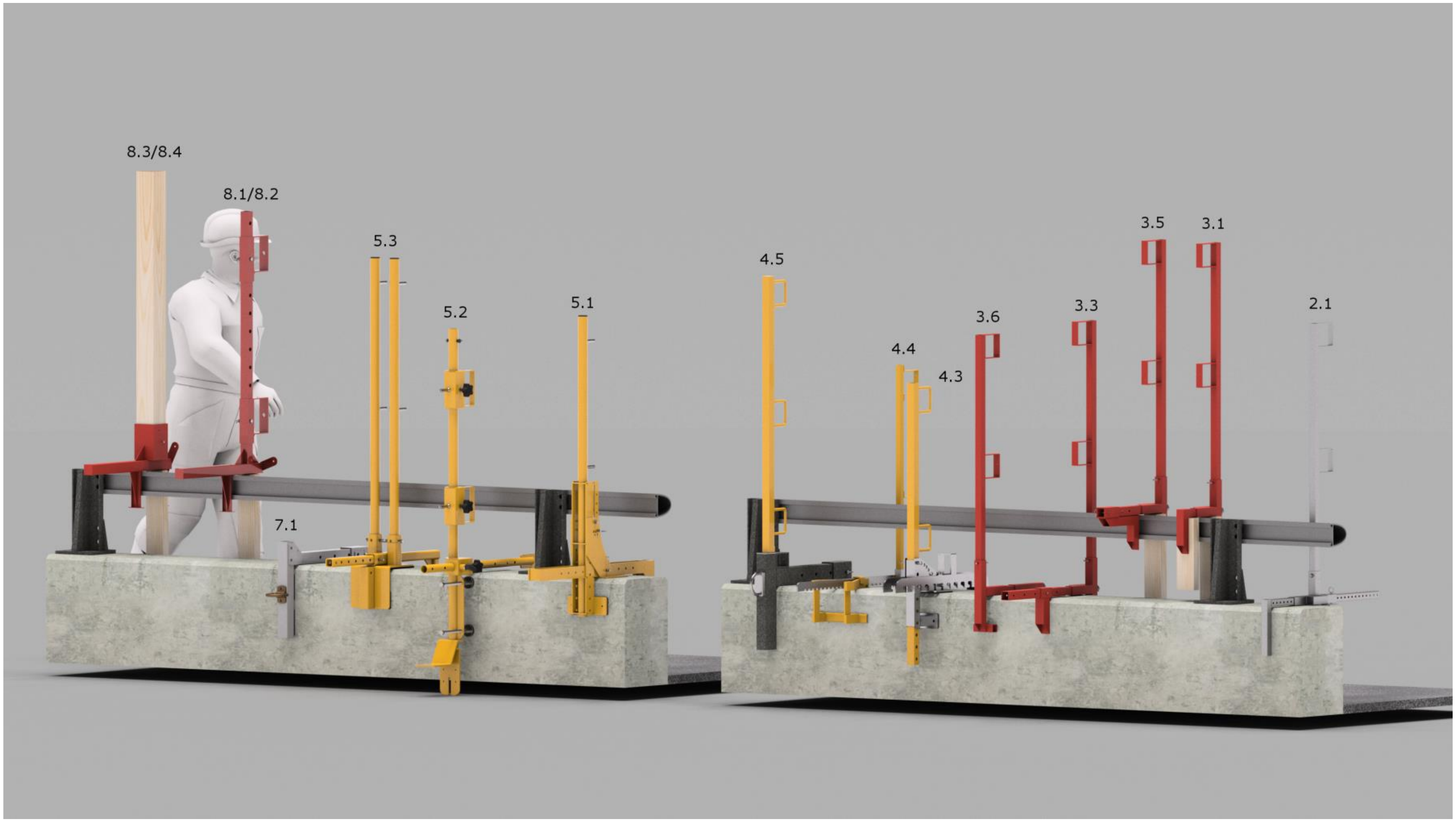


Figure 9 – Guardrail Type 01; view from the southwest

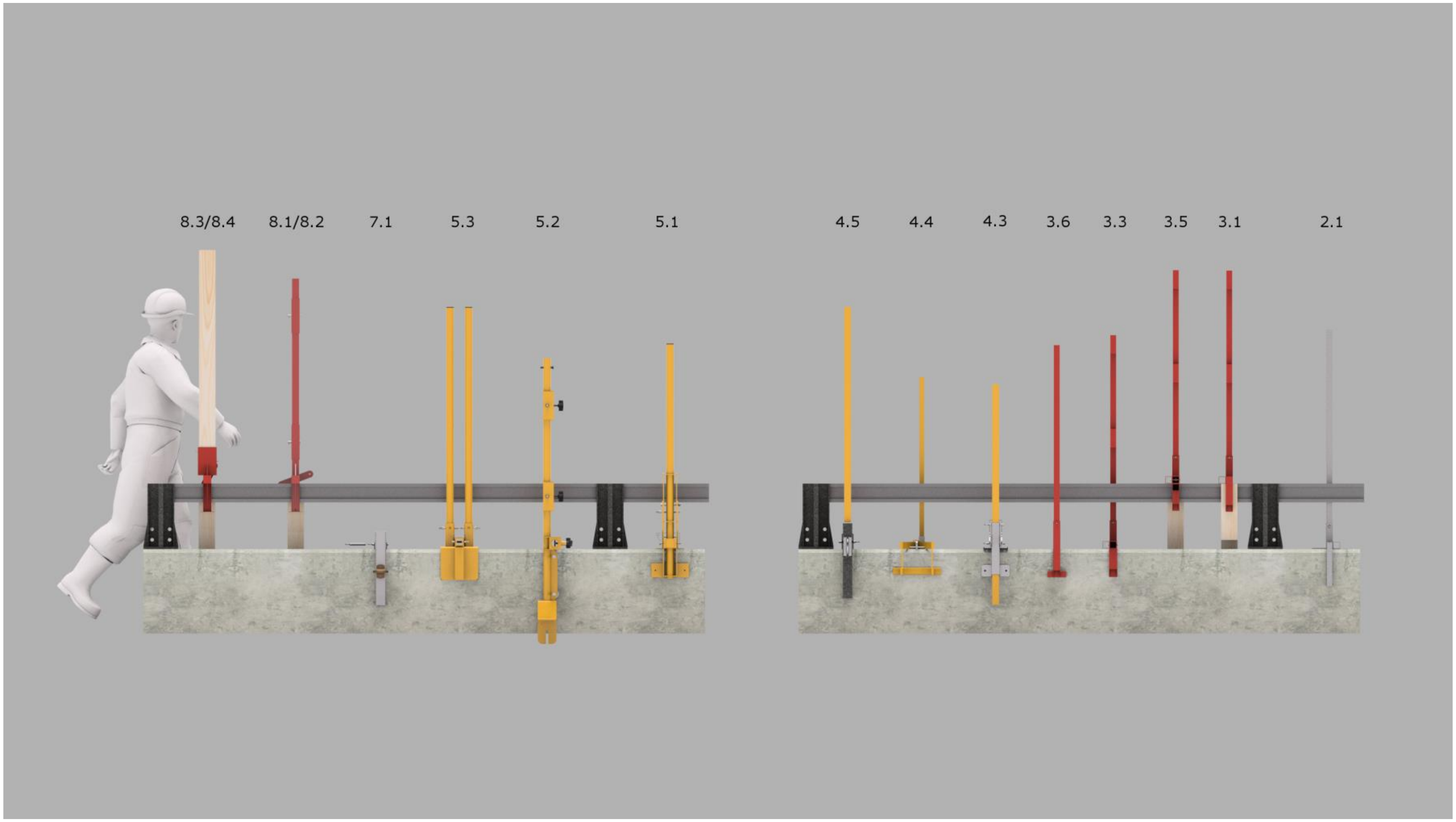


Figure 10 – Guardrail Type 01; view from the west

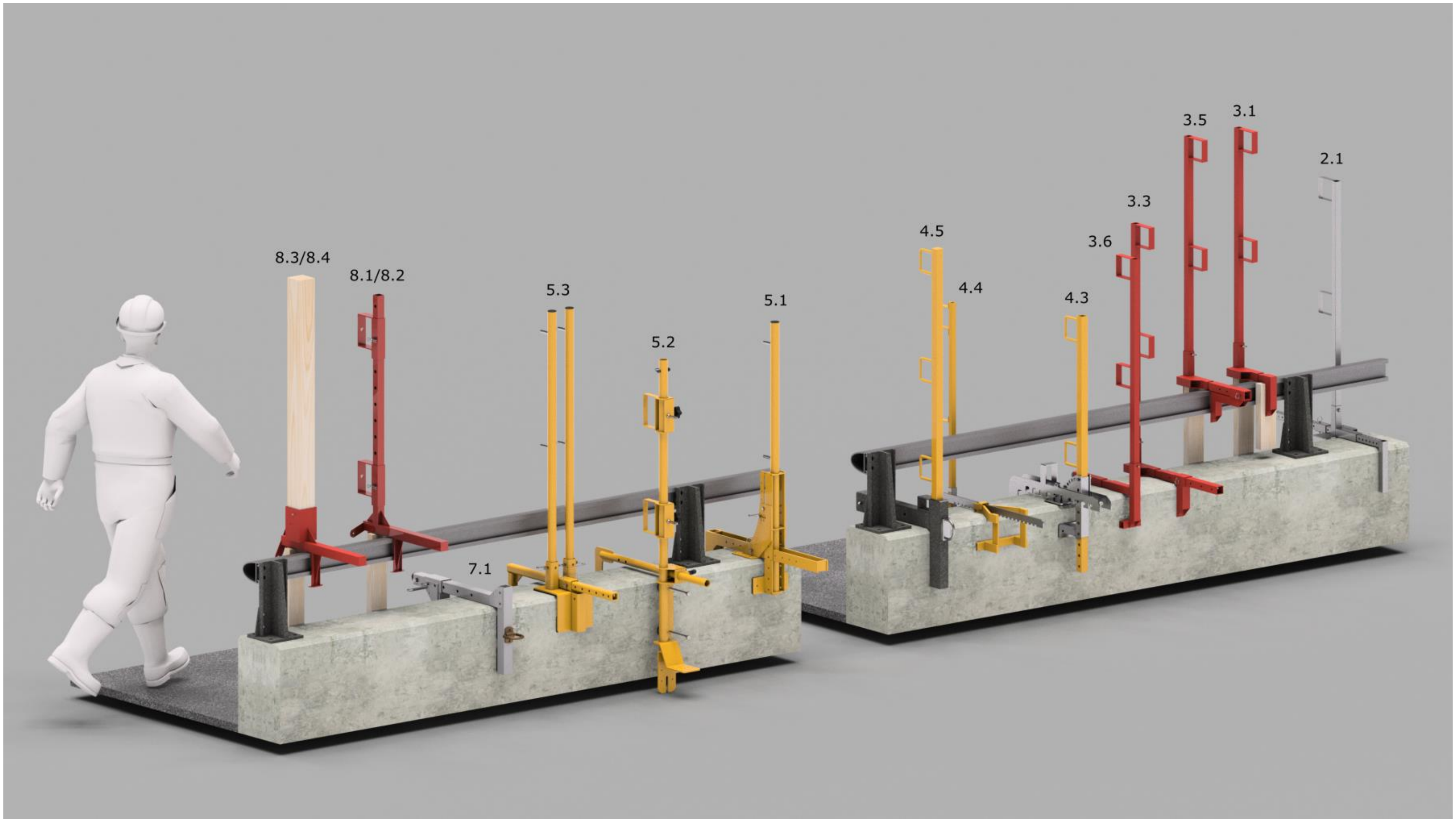


Figure 11 – Guardrail Type 01; view from the northwest

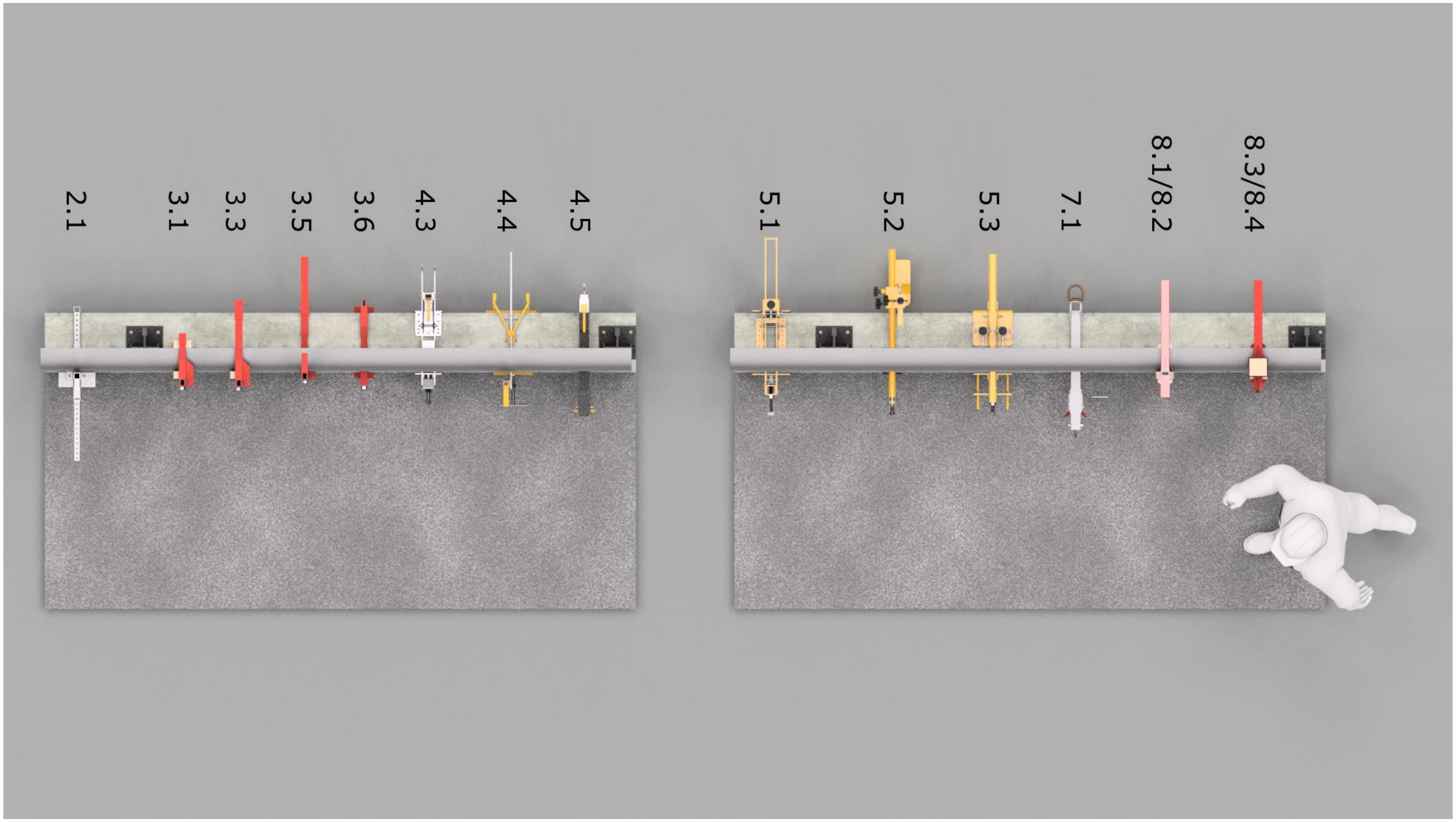


Figure 12 – Guardrail Type 01; view from the top

4. GUARDRAIL TYPE 02 – 1-Bar Concrete Rail (Top)

4.1 Description

Concrete guardrail sections comprised of one reinforced concrete railing bar atop two reinforced concrete supports, one at each end, as shown in Figure 13.

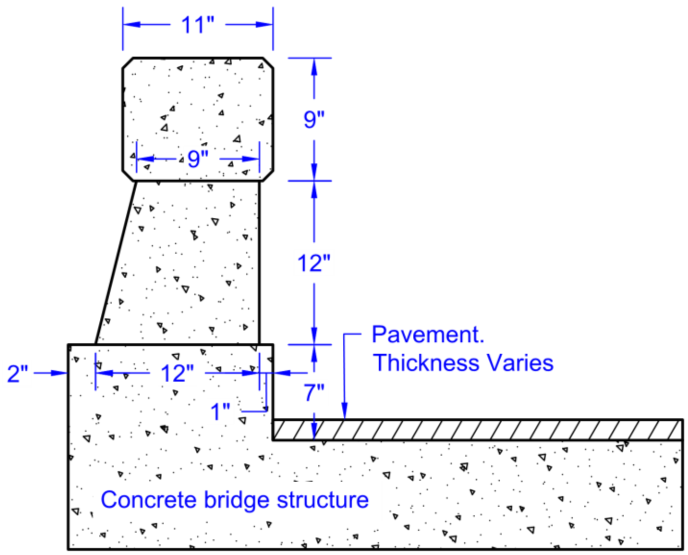


Figure 13 – Guardrail Type 02 section

4.2 Compatibility Chart

Table 3 – Compatibility chart for Guardrail Type 02

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it intrudes the least into the work area (approximately 5.5”).
3.1	C-Clamp - CC120	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it intrudes the least into the work area (approximately 2.25”).
3.3	Master C-Clamp - MCC130	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it intrudes the least into the work area (approximately 2.25”).
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 6.75”
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 6.75”
4.5	Parapet Anchor - 15171	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 10”
5.1	RaptorRail	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75”
5.2	All-In-One	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75”
5.3	Universal Guardrail Parapet Clamp	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it offer the easiest and most convenient installation. Intrusion into the work area is approximately 8.75”

ID	PRODUCT NAME	COMPATIBILITY NOTES
8.1	Parapet Guardrails GRS-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.2	Parapet Guardrails GRS-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.3	QuickRail Parapet Guardrail QR-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.4	QuickRail Parapet Guardrail QR-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”

4.3 Renderings

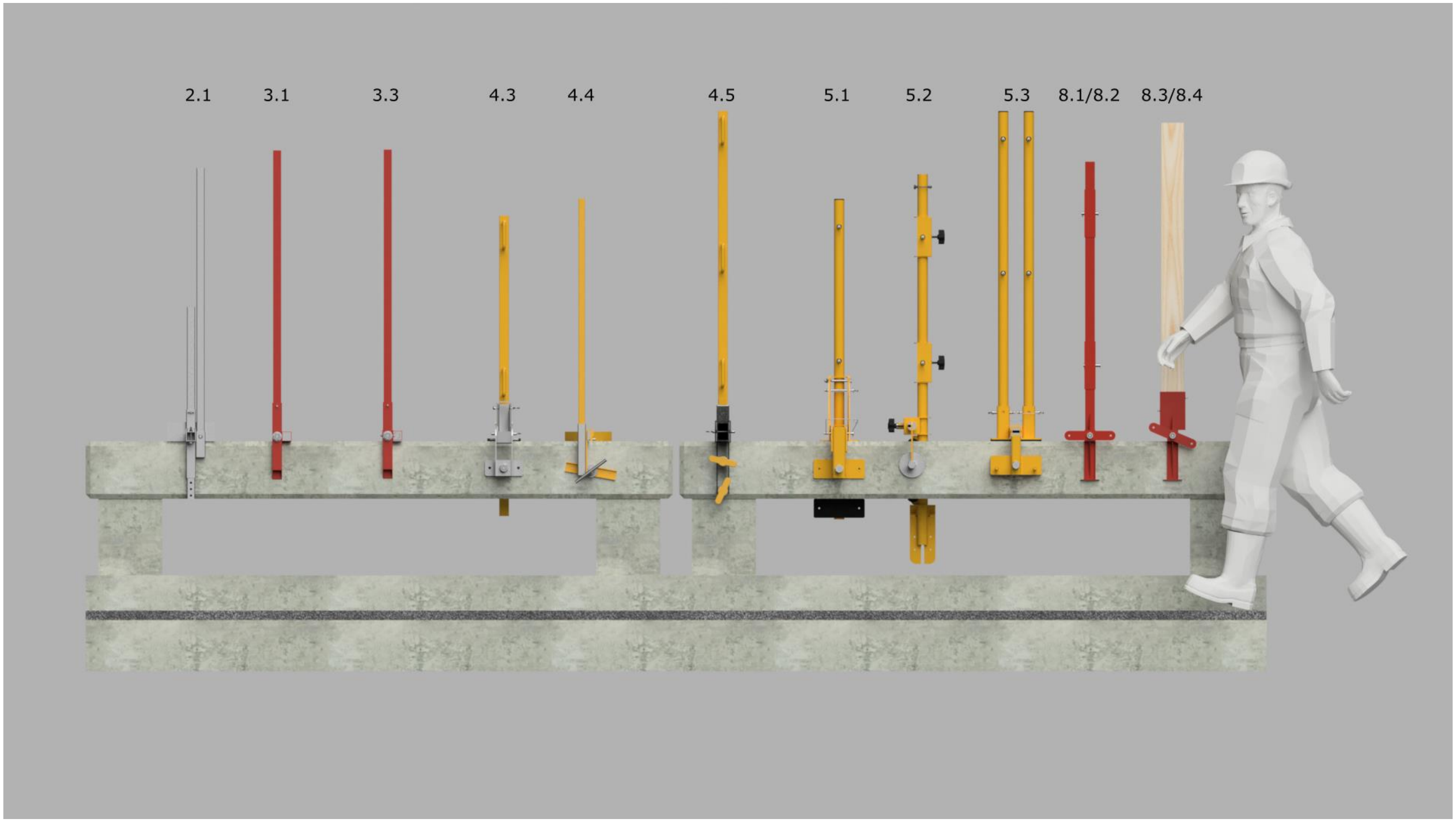


Figure 14 – Guardrail Type 02; view from the east

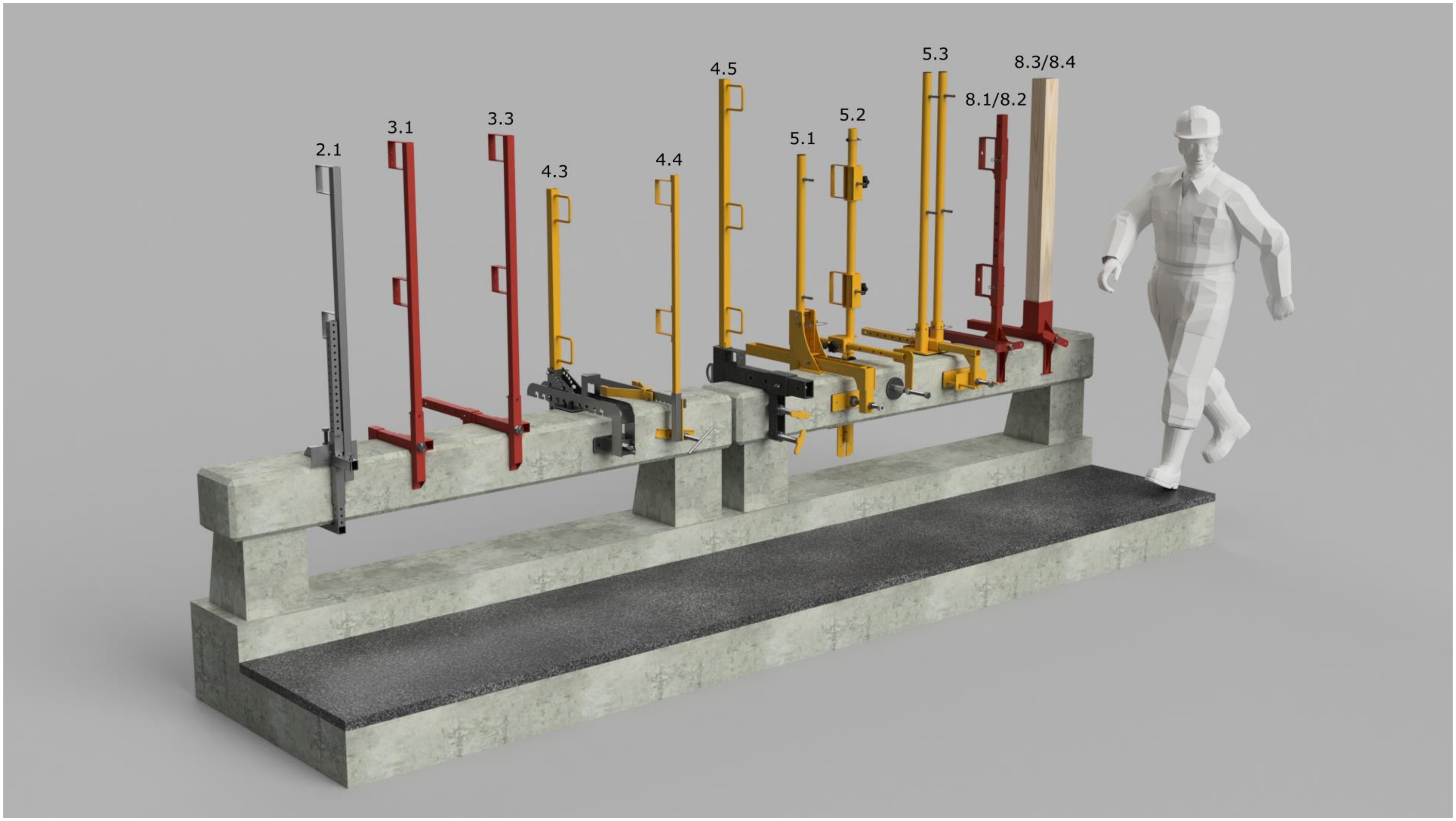


Figure 15 – Guardrail Type 02; view from the southeast

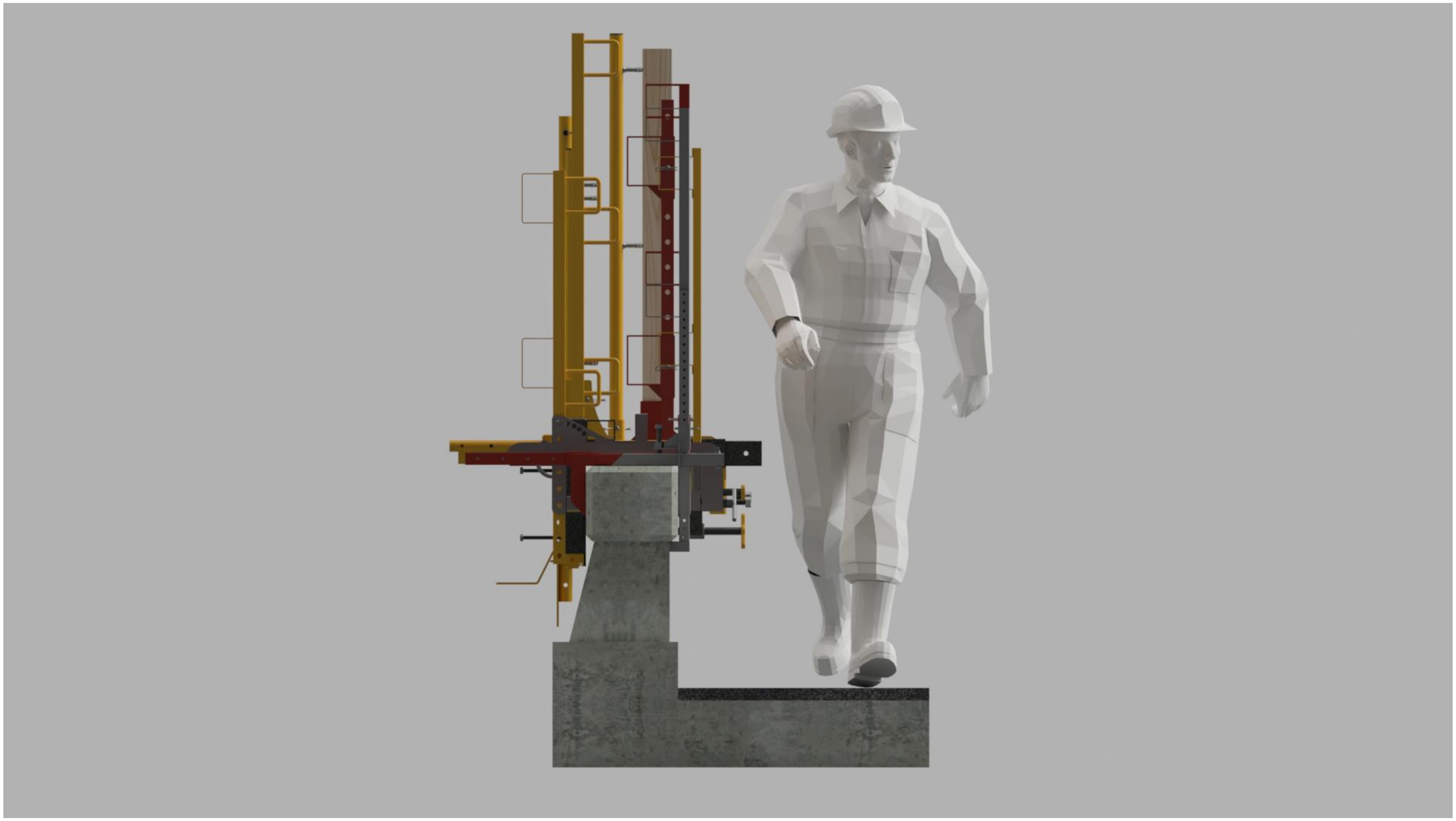


Figure 16 – Guardrail Type 02; view from the south

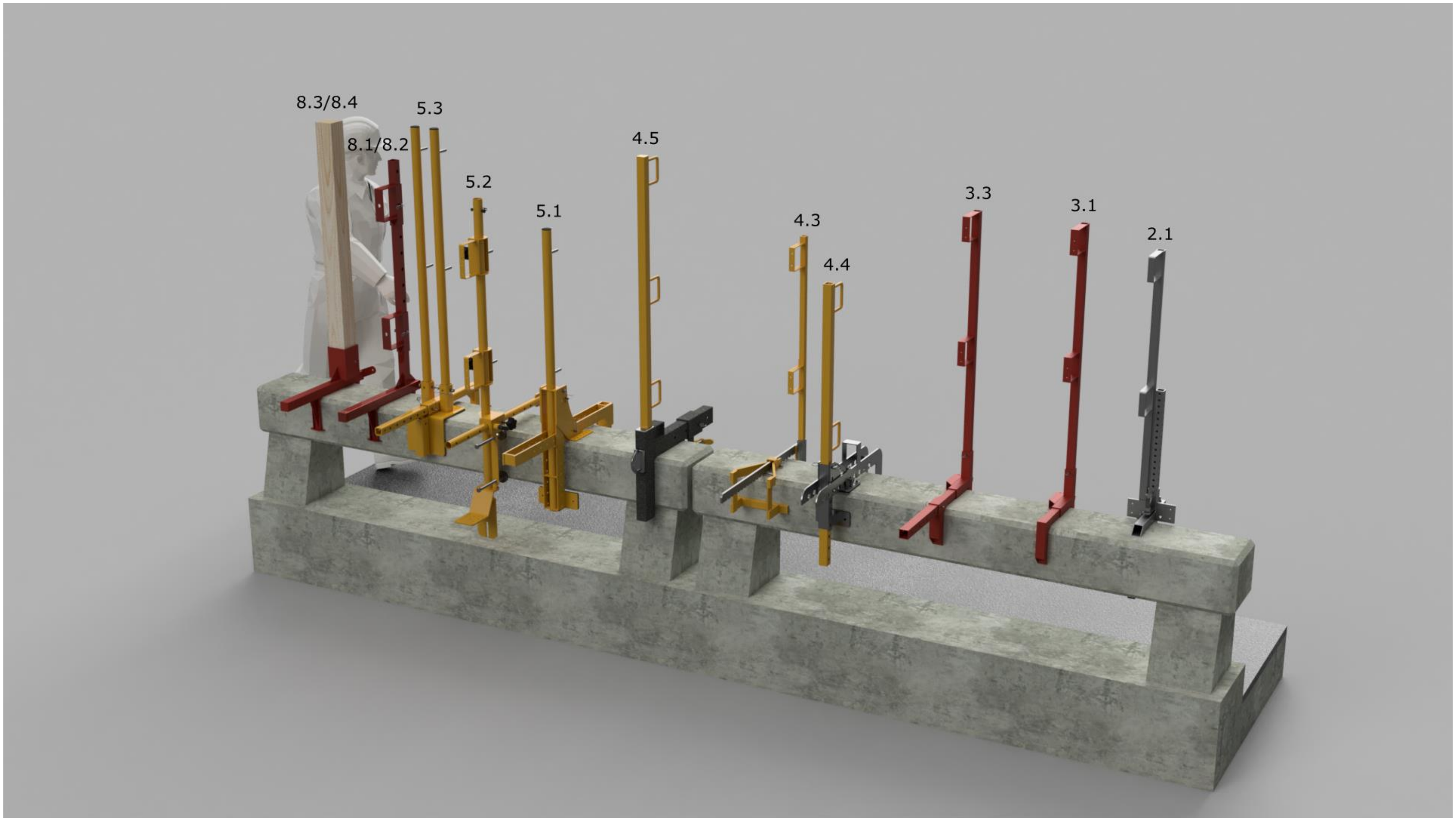


Figure 17 – Guardrail Type 02; view from the southwest

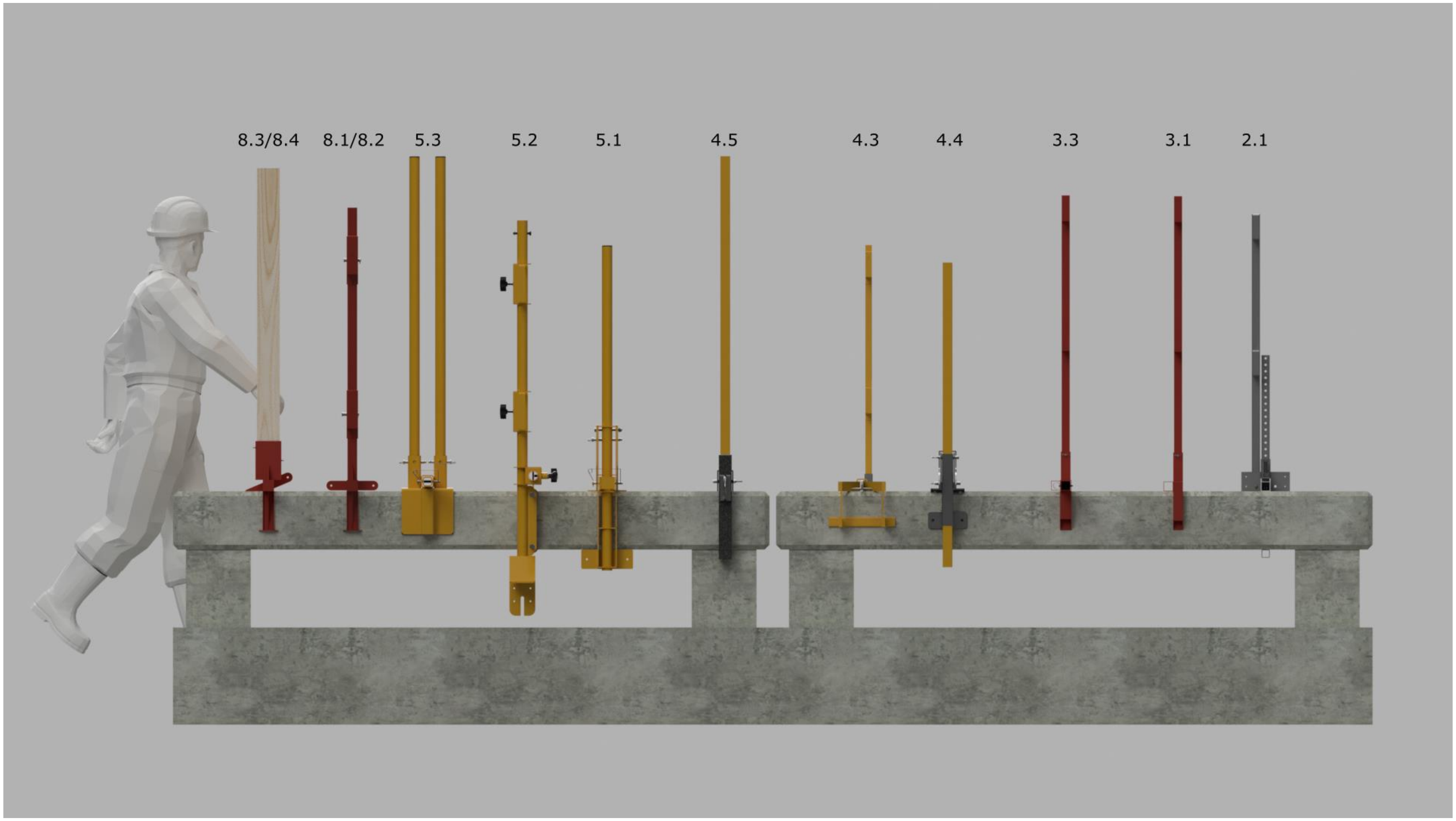


Figure 18 – Guardrail Type 02; view from the west

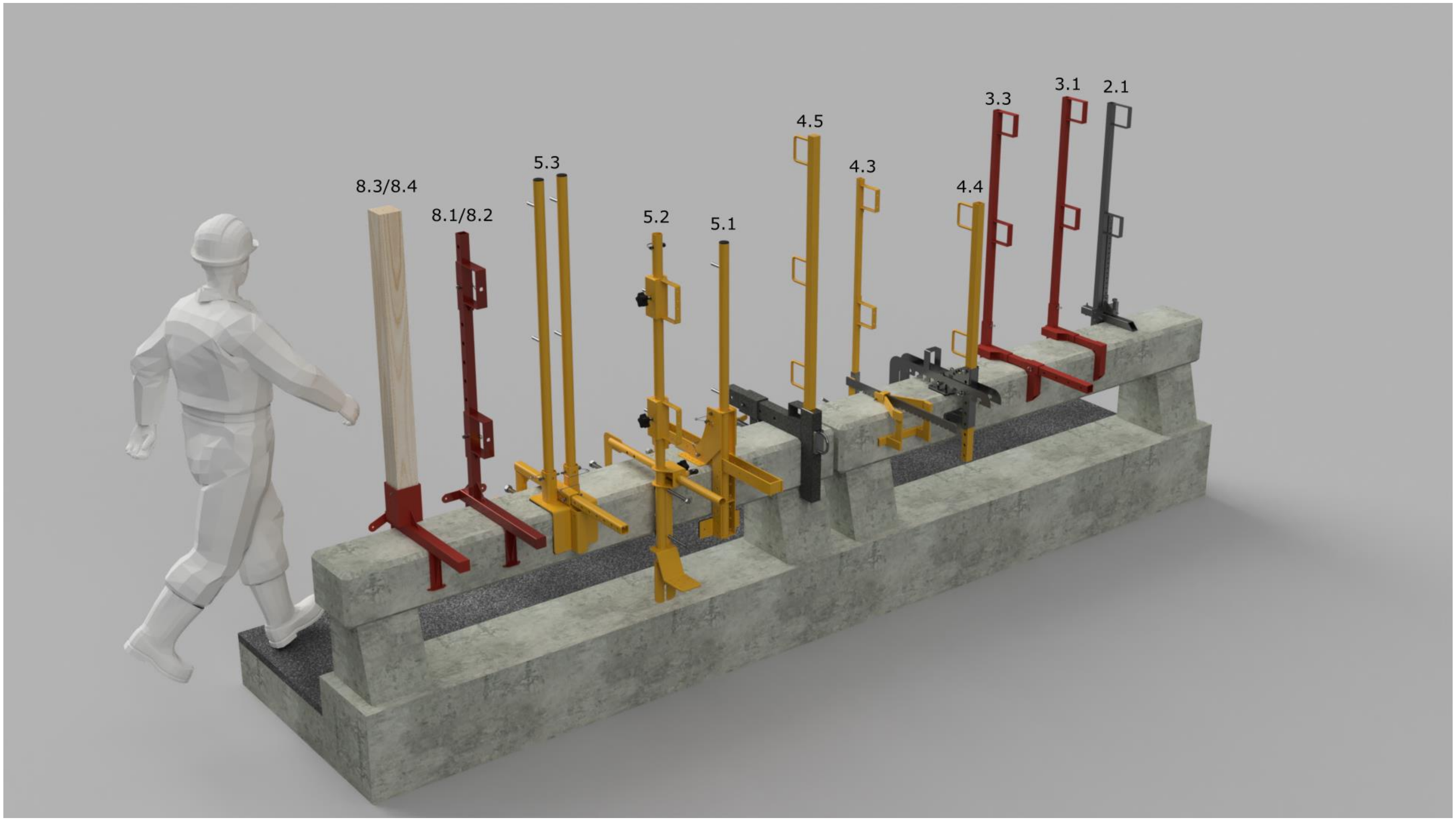


Figure 19 – Guardrail Type 02; view from the northwest

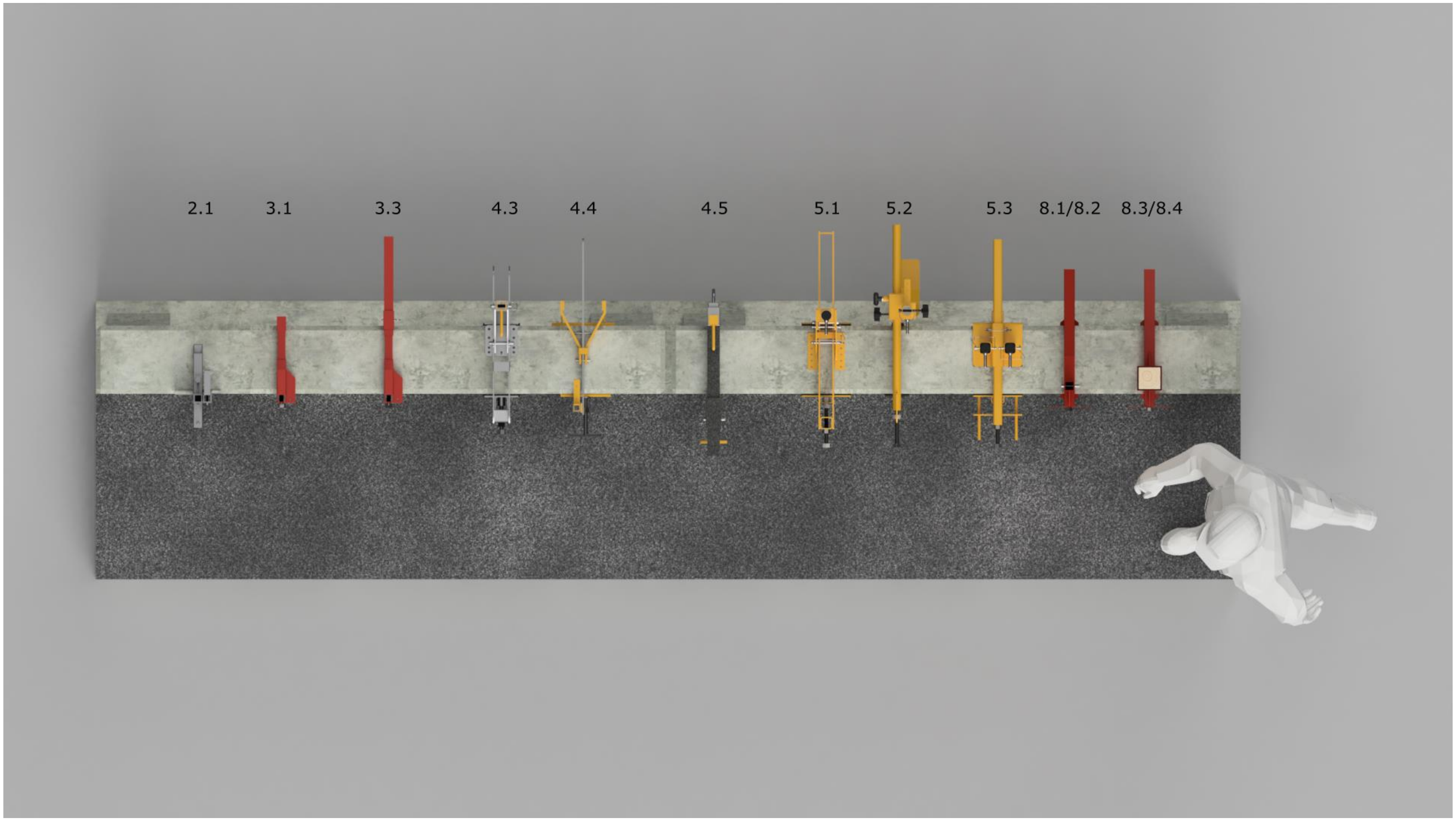


Figure 20 – Guardrail Type 02; view from the top

5. GUARDRAIL TYPE 04 – Jersey Barrier

5.1 Description

Commonly referred to as "Jersey Barrier", this guardrail comprised of a single reinforced concrete section with flat rear and sloping surfaces in the front. After gathering data in the Wiggins database, we found two variations of this guardrail type as shown in Figure 21 and Figure 22. For the purposes of this report, only variation 2 was studied as the lower height represents a greater risk for the workers on the bridge deck.

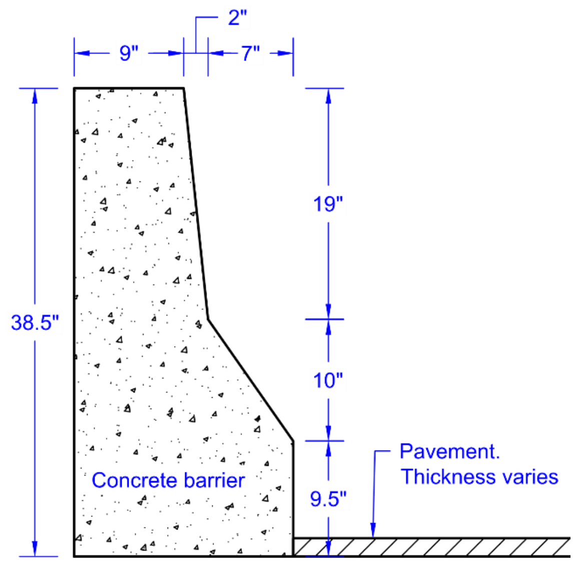


Figure 21 - Guardrail Type 04 section, variation 1

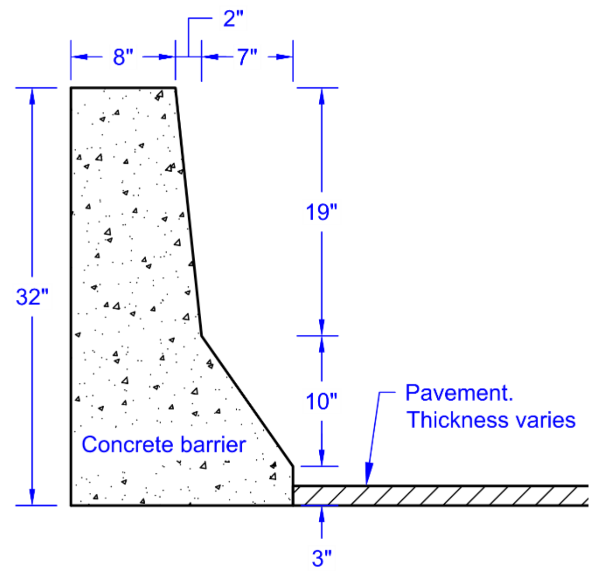


Figure 22 - Guardrail Type 04 section, variation 2

5.2 Compatibility Chart

Table 4 - Compatibility chart for Guardrail Type 04

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the parapet. Intrusion into the work area is approximately 13".
3.1	C-Clamp - CC120	The device fits over the parapet. There is no intrusion into the work area.
3.3	Master C-Clamp - MCC130	This device fits over the concrete parapet. There is no intrusion into the work area
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the concrete parapet. There is no intrusion into the work area.
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the concrete parapet. There is no intrusion into the work area.
4.5	Parapet Anchor - 15171	This device fits the concrete parapet. Intrusion into the work area is approximately 4".
5.1	RaptorRail	This device fits over the concrete parapet. Intrusion into the work area is approximate 0.75".
5.2	All-In-One	This device fits over the concrete parapet. There is no intrusion into the work area.
5.3	Universal Guardrail Parapet Clamp	This device fits over the concrete parapet. Intrusion into the work area is approximate 0.75".
8.1	Parapet Guardrails GRS-P12	The device fits over the parapet. There is no intrusion into the work area.

ID	PRODUCT NAME	COMPATIBILITY NOTES
8.2	Parapet Guardrails GRS-P24	The device fits over the parapet. There is no intrusion into the work area.
8.3	QuickRail Parapet Guardrail QR-P12	The device fits over the parapet. There is no intrusion into the work area.
8.4	QuickRail Parapet Guardrail QR-P24	The device fits over the parapet. There is no intrusion into the work area.

5.3 Renderings

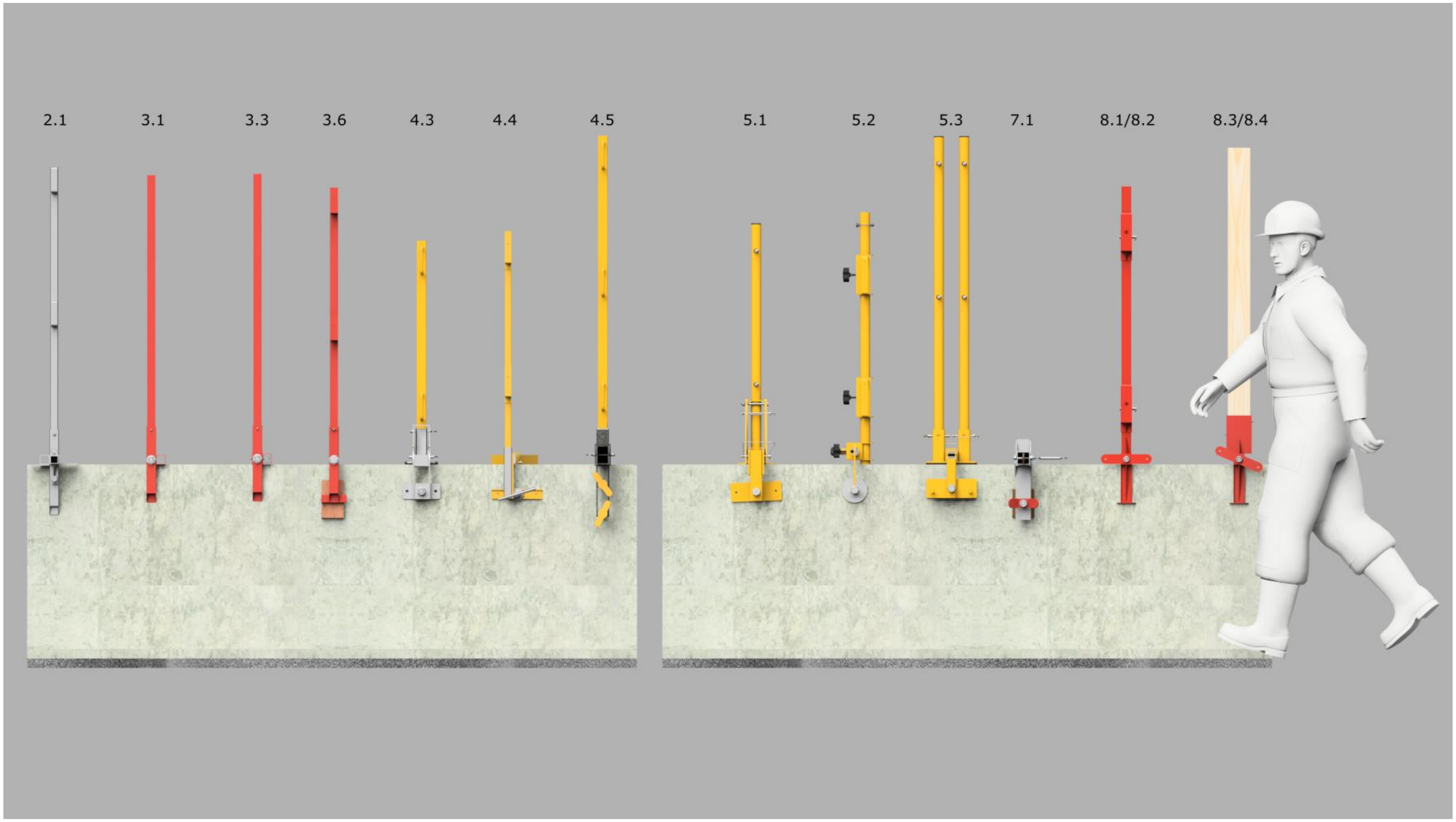


Figure 23 – Guardrail Type 04; view from the east

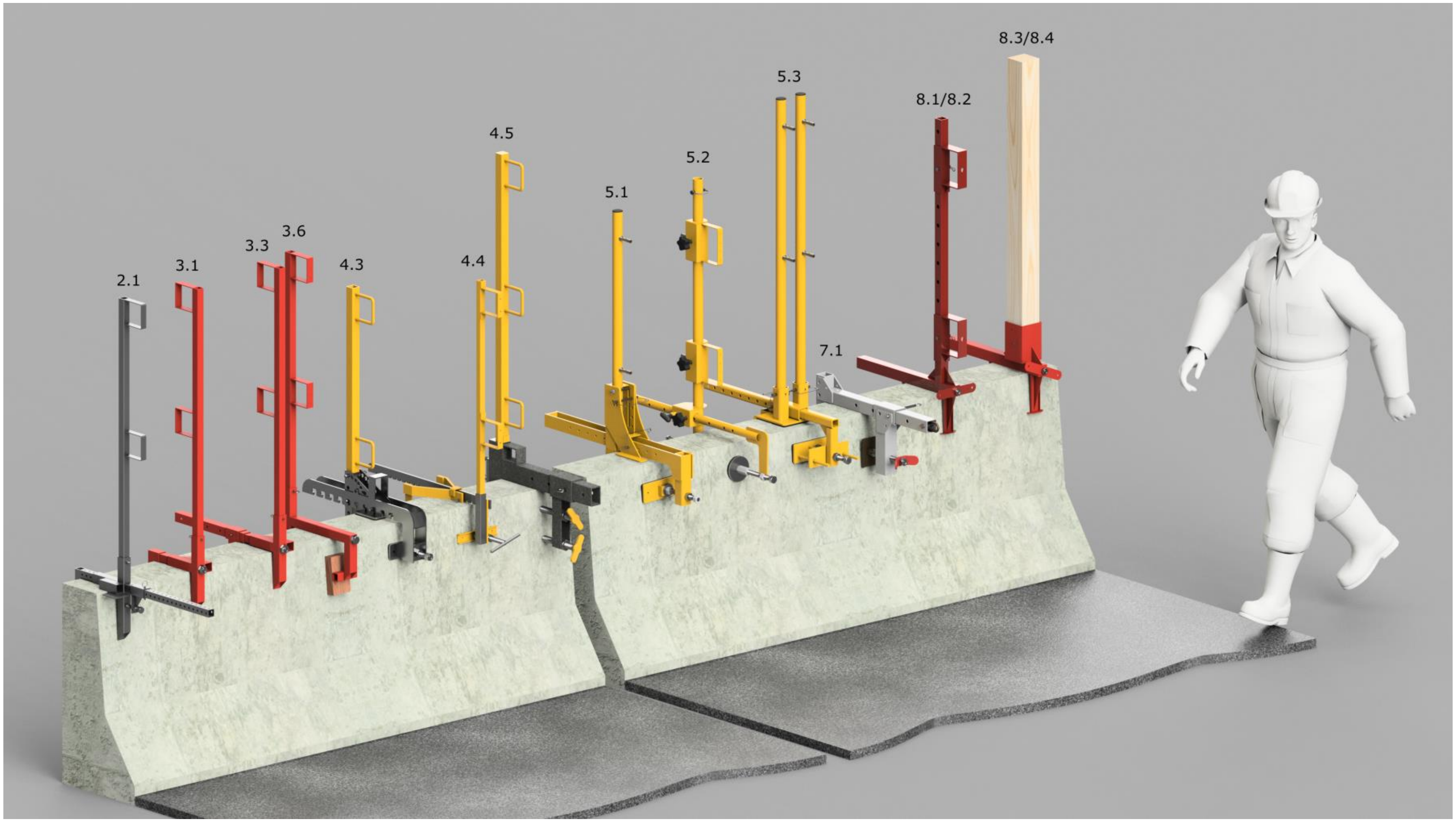


Figure 24 - Guardrail Type 04; view from the southeast

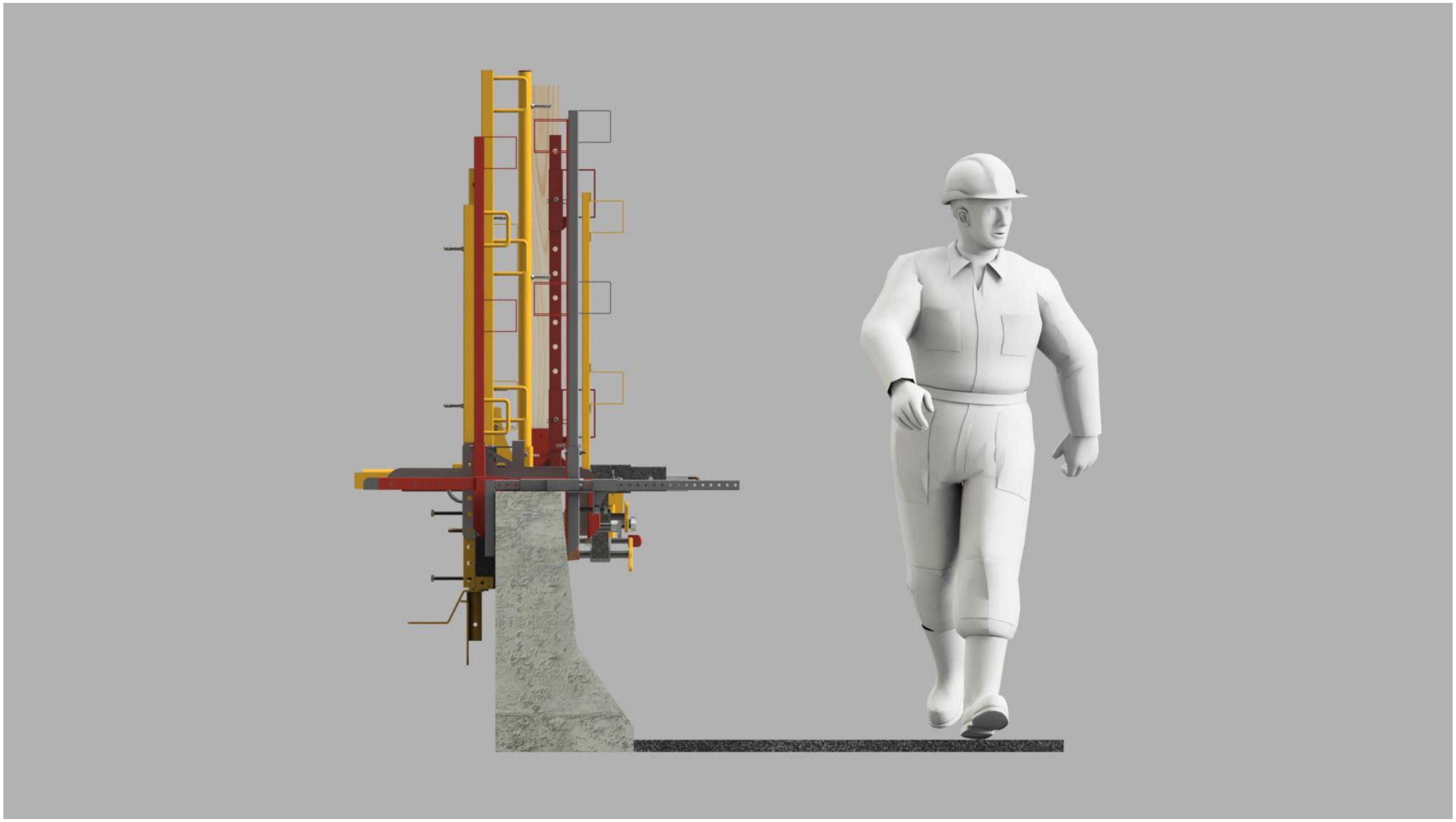


Figure 25 – Guardrail Type 04; view from the south

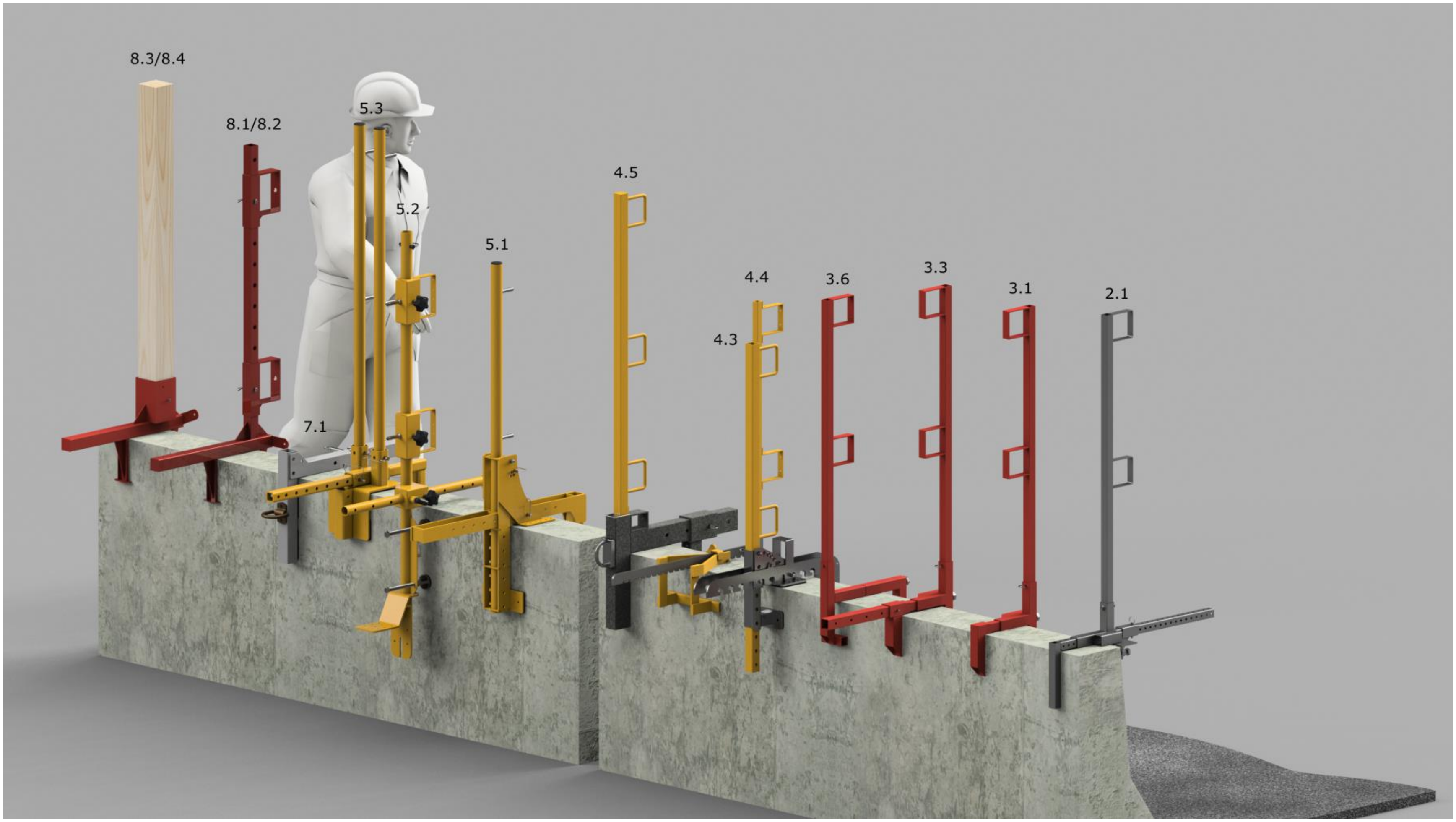


Figure 26 – Guardrail Type 04; view from the southwest

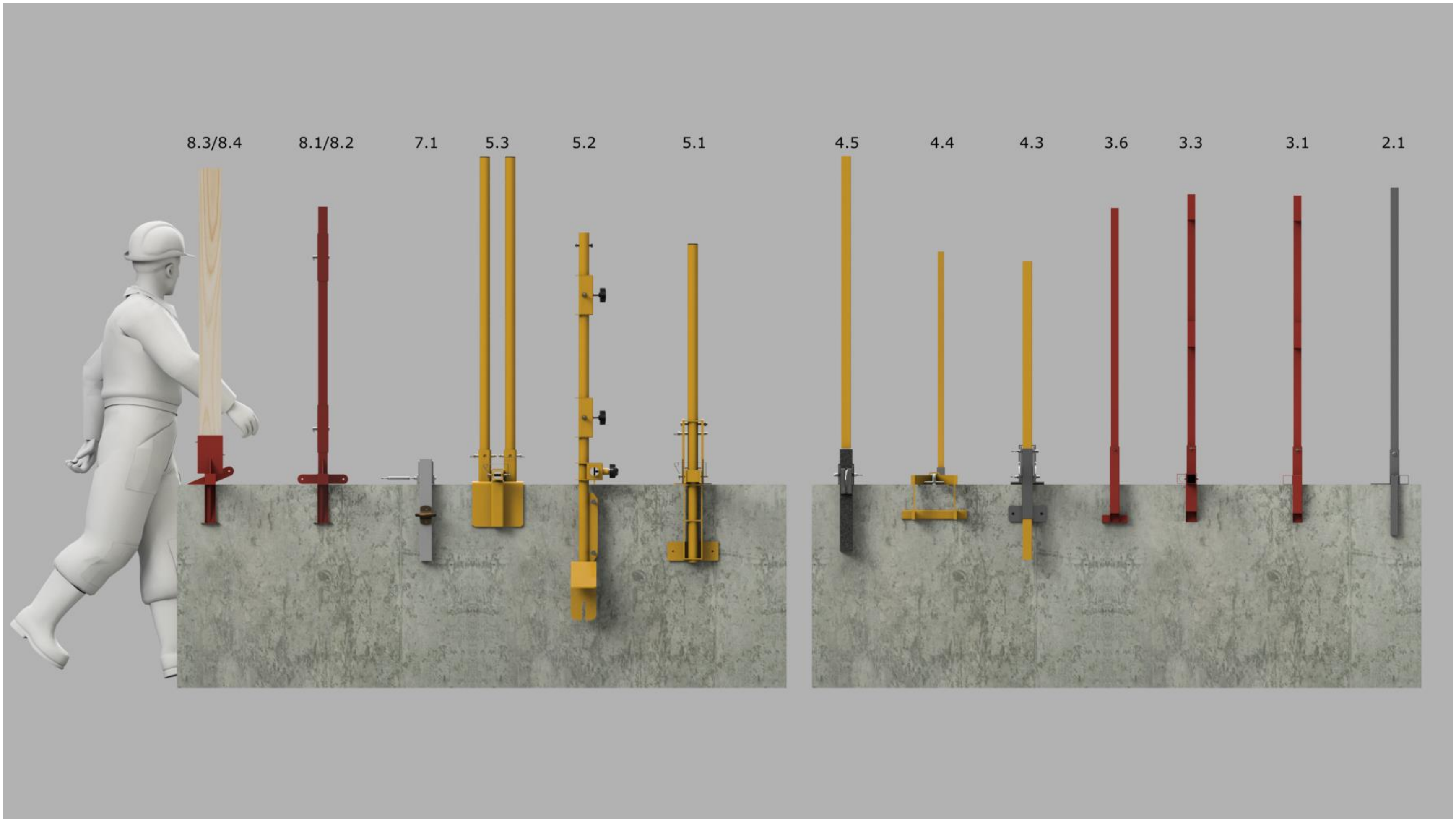


Figure 27 – Guardrail Type 04; view from the west

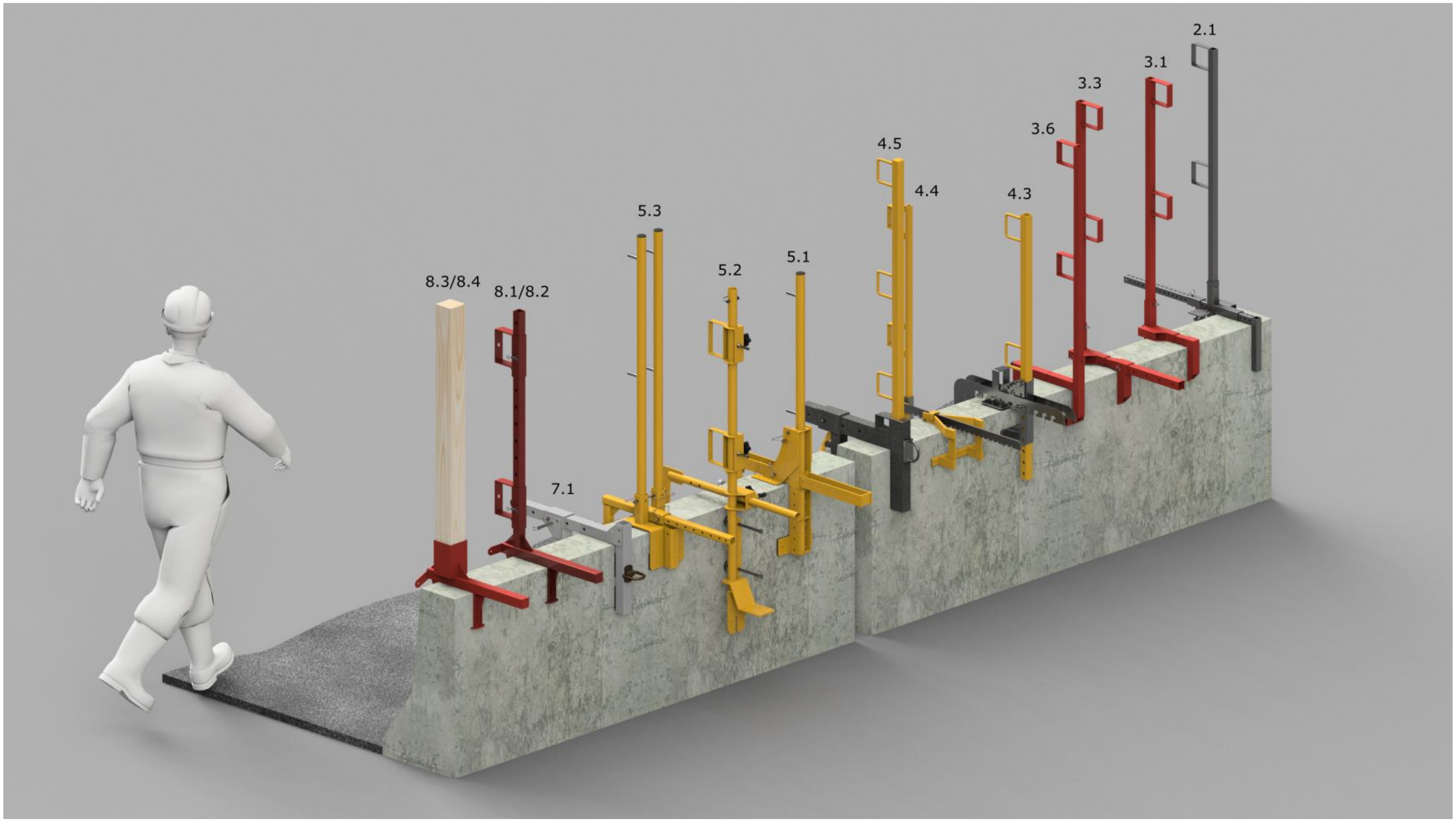


Figure 28 – Guardrail Type 04; view from the northwest

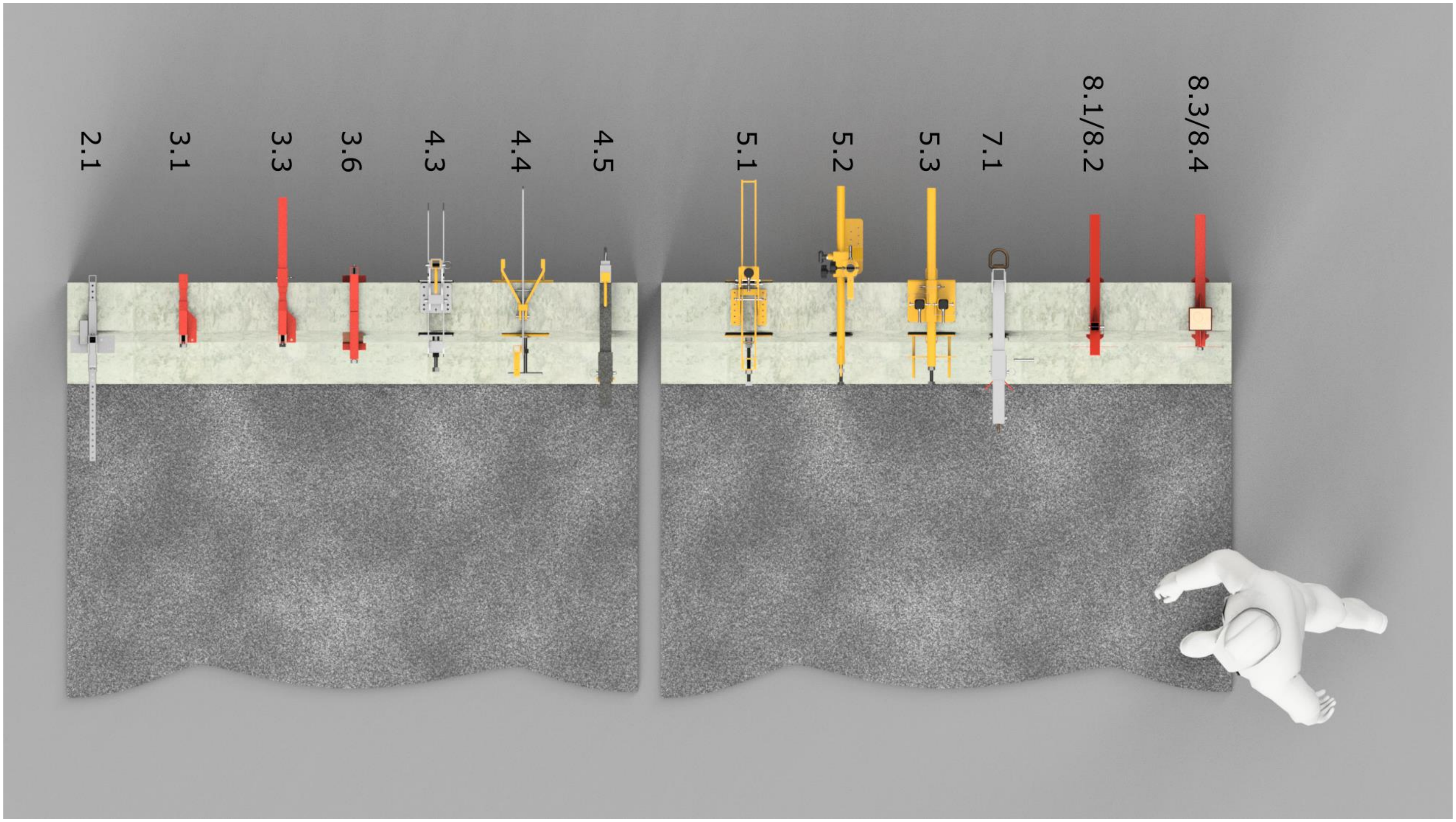


Figure 29 – Guardrail Type 04; view from the top

6. GUARDRAIL TYPE 07 – 1-Bar Concrete Rail (Top)

6.1 Description

Concrete guardrail sections comprised of one reinforced concrete railing bar atop two reinforced concrete supports, one at each end. A section of this guardrail is shown in Figure 30.

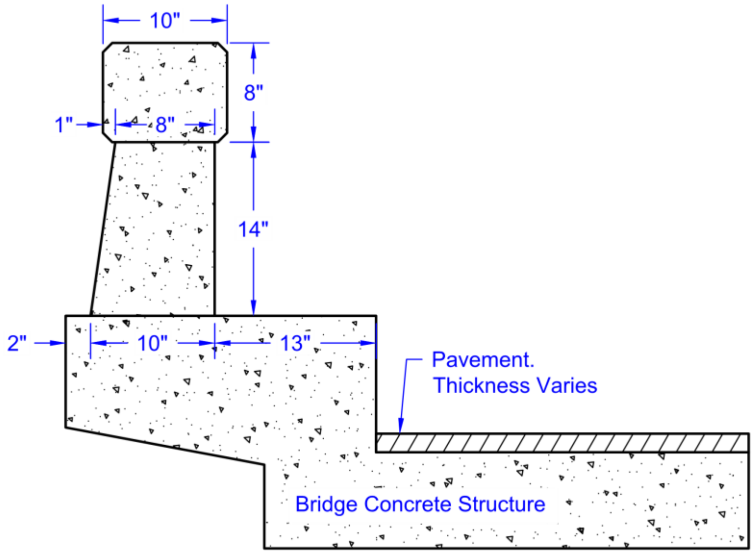


Figure 30 – Guardrail Type 07 section

6.2 Compatibility Chart

Table 5 – Compatibility chart for Guardrail Type 07

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as slab clamp as it intrudes the least into the work area (approximately 5.5”).
3.1	C-Clamp - CC120	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it intrudes the least into the work area (approximately 2.25”).
3.3	Master C-Clamp - MCC130	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.25”
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 6.5”
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 7”
4.5	Parapet Anchor - 15171	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 11”
5.1	RaptorRail	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75”
5.2	All-In-One	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75”
5.3	Universal Guardrail Parapet Clamp	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it offer the easiest and most convenient installation. Intrusion into the work area is approximately 8.75”
8.1	Parapet Guardrails GRS-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”

ID	PRODUCT NAME	COMPATIBILITY NOTES
8.2	Parapet Guardrails GRS-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.3	QuickRail Parapet Guardrail QR-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.4	QuickRail Parapet Guardrail QR-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”

6.3 Renderings

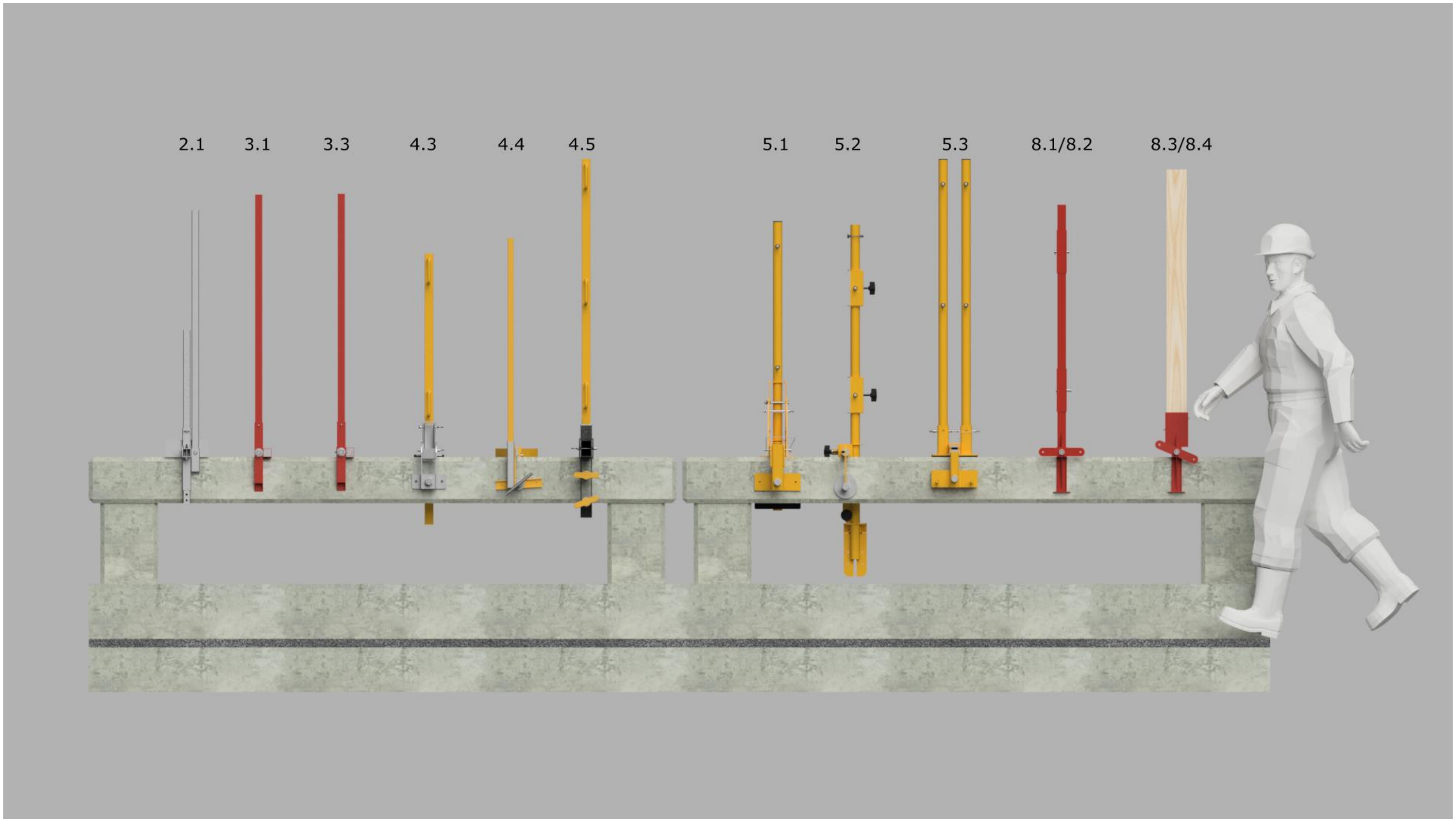


Figure 31 – Guardrail Type 07; view from the east

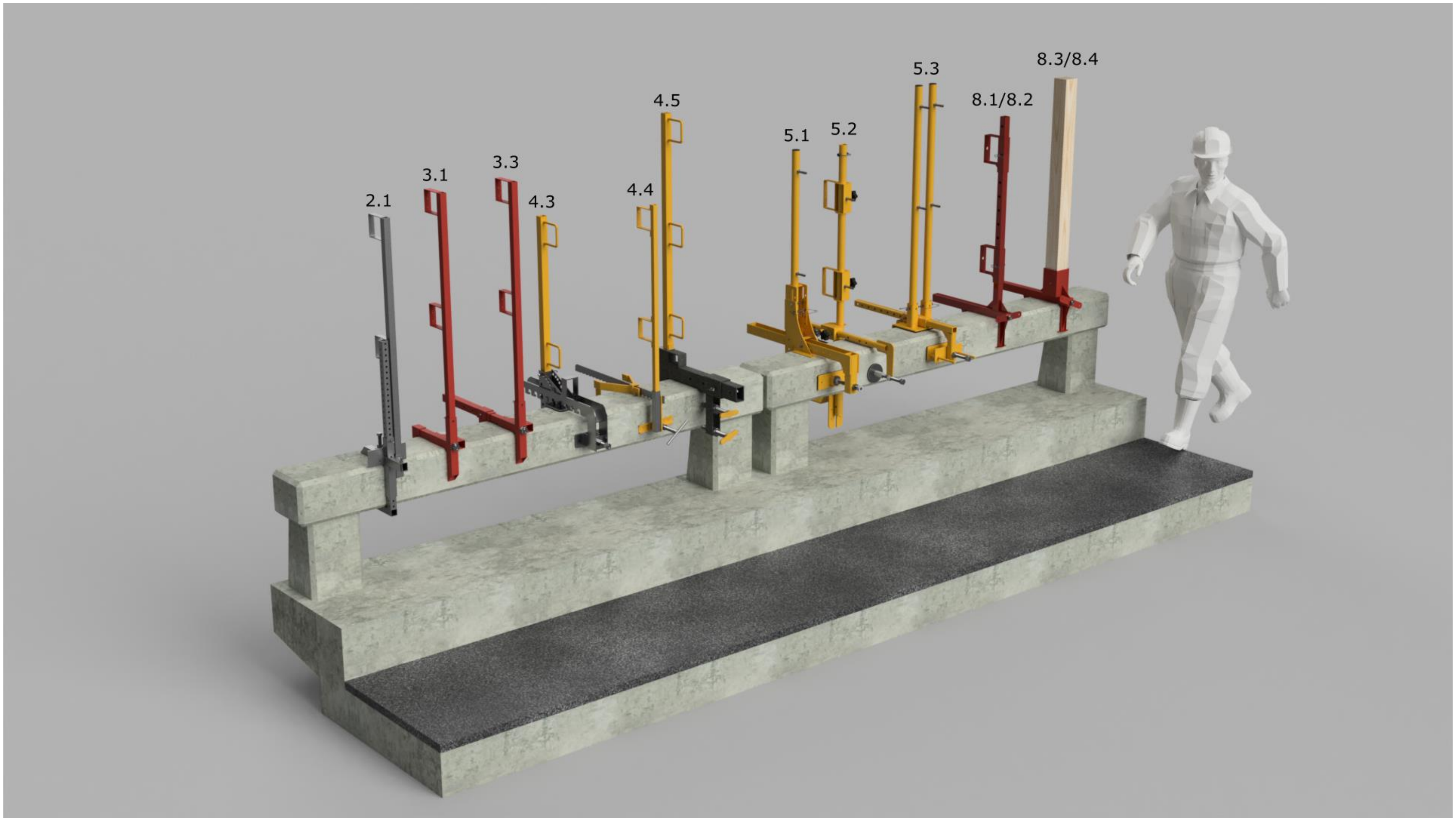


Figure 32 – Guardrail Type 07; view from the southeast


Figure 33 – Guardrail Type 07; view from the south

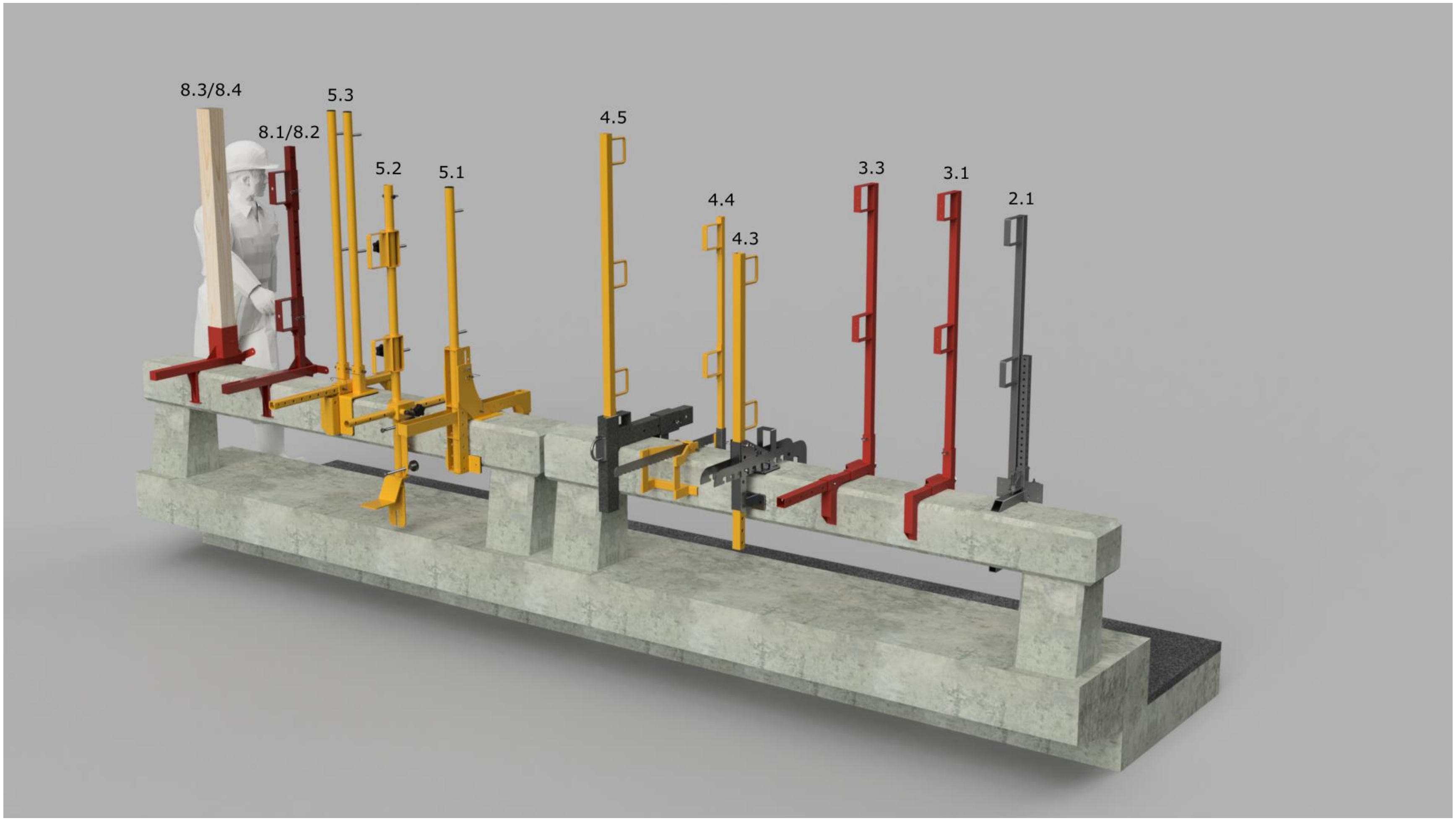


Figure 34 – Guardrail Type 07; view from the southwest

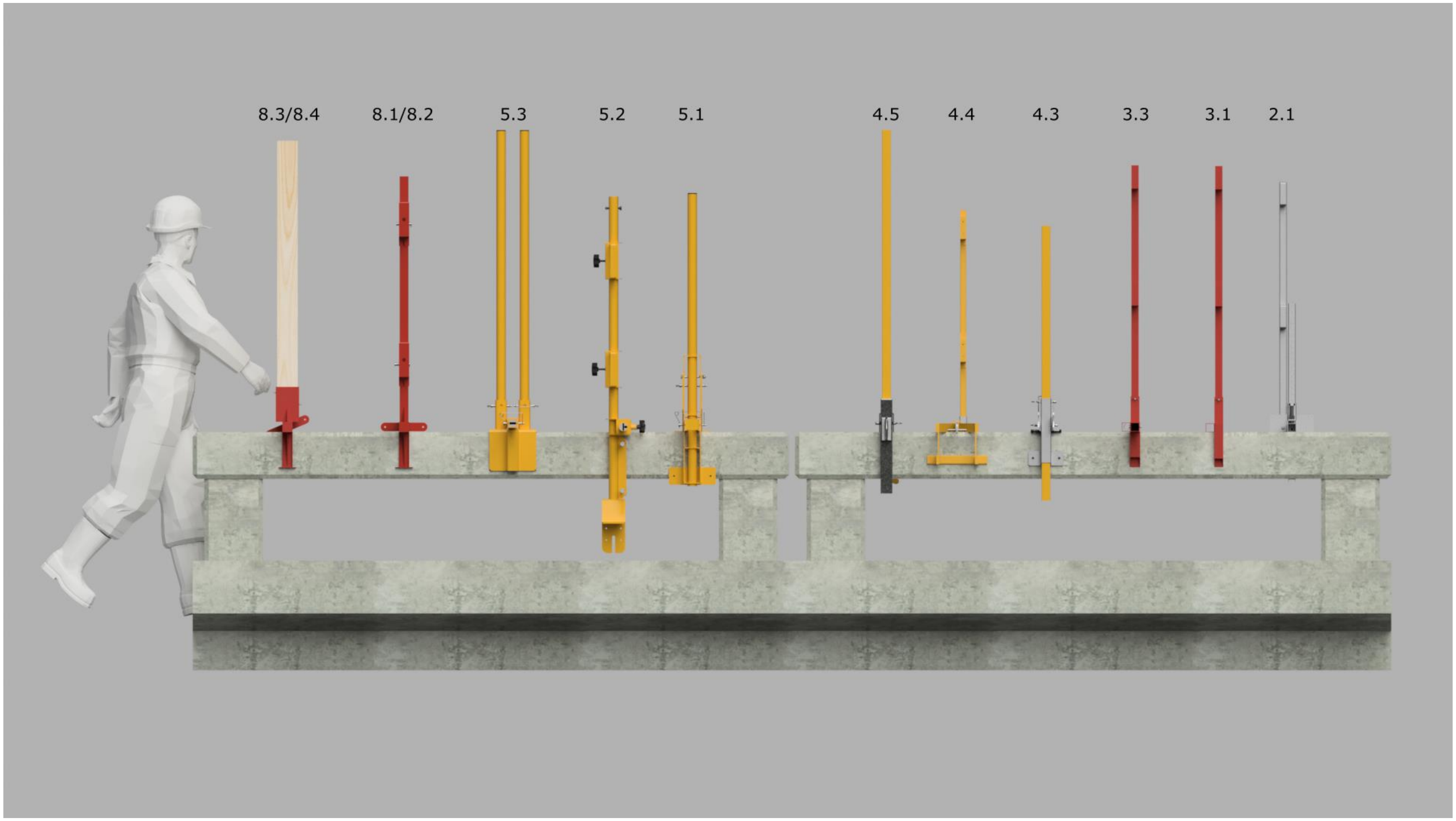


Figure 35 – Guardrail Type 07; view from the west

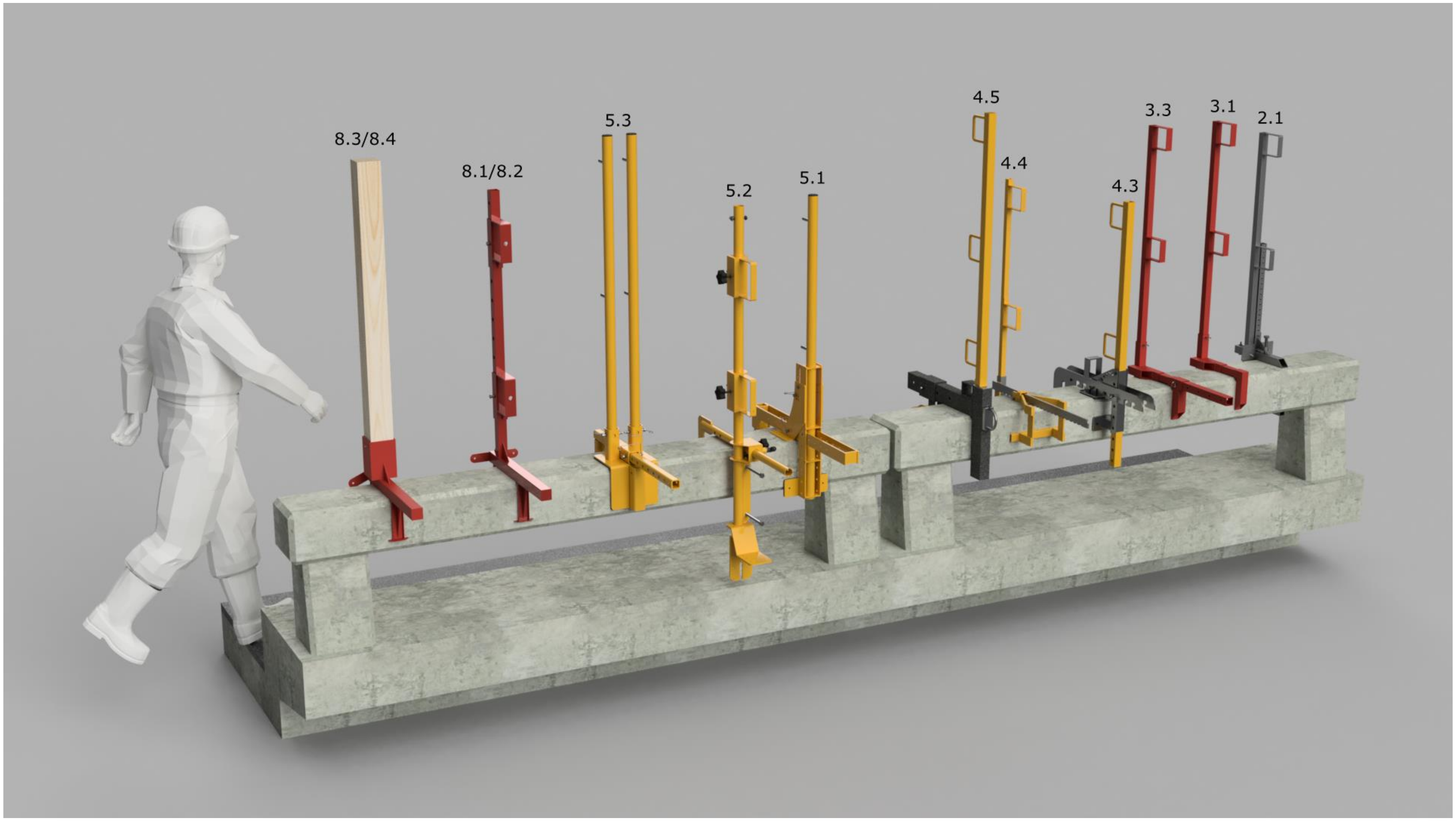


Figure 36 – Guardrail Type 07; view from the northwest

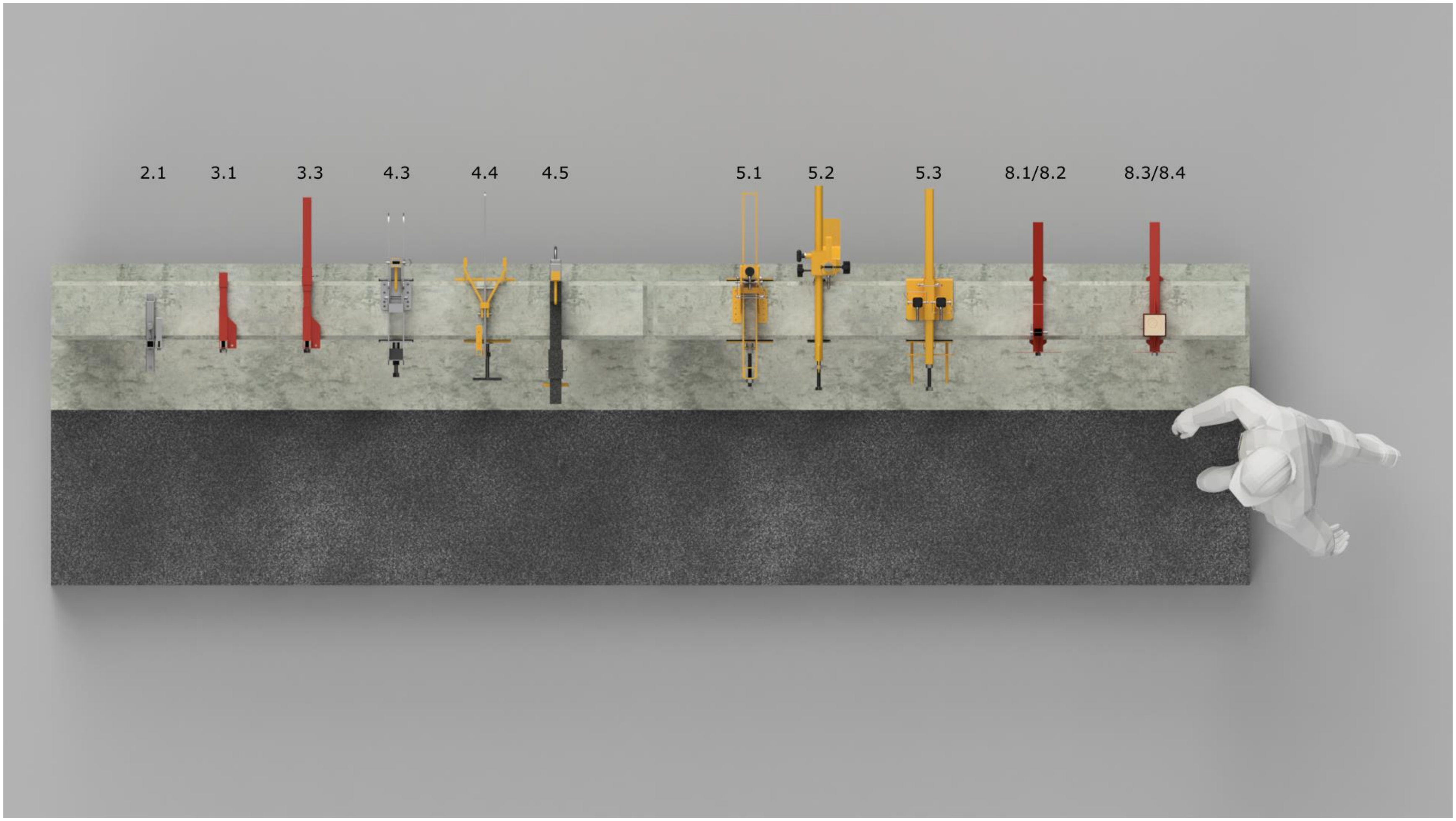


Figure 37 – Guardrail Type 07; view from the top

7. GUARDRAIL TYPE 11 – 1-Bar Concrete Rail (Middle)

7.1 Description

Concrete guardrail sections comprised of one reinforced concrete railing embedded at mid-height into two reinforced concrete supports, one at each end, as shown in Figure 38.

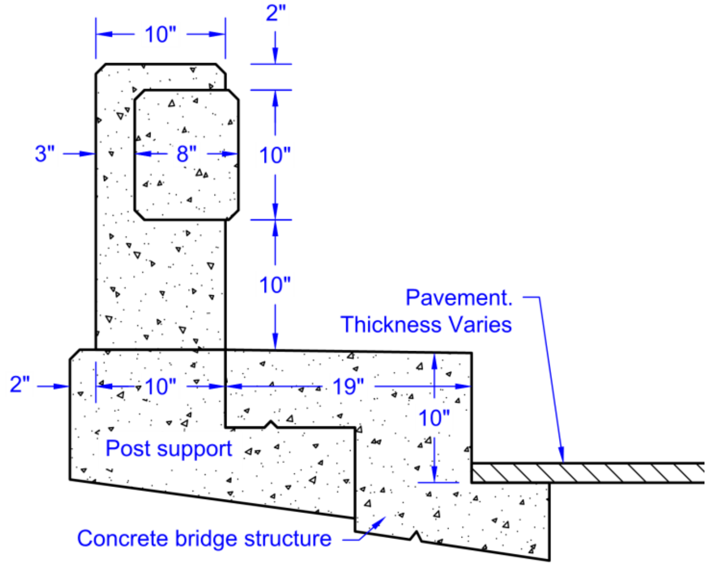


Figure 38 – Guardrail Type 11 section

7.2 Compatibility Chart

Table 6 – Compatibility chart for Guardrail Type 11

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as slab clamp as it intrudes the least into the work area (approximately 5.5”).
3.1	C-Clamp - CC120	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it intrudes the least into the work area (approximately 2.25”).
3.3	Master C-Clamp - MCC130	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.25”
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 6.5”
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 7”
4.5	Parapet Anchor - 15171	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 13”
5.1	RaptorRail	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.5”
5.2	All-In-One	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.5”
5.3	Universal Guardrail Parapet Clamp	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it offer the easiest and most convenient installation. Intrusion into the work area is approximately 8.75”
8.1	Parapet Guardrails GRS-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”

ID	PRODUCT NAME	COMPATIBILITY NOTES
8.2	Parapet Guardrails GRS-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.3	QuickRail Parapet Guardrail QR-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.4	QuickRail Parapet Guardrail QR-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”

7.3 Renderings

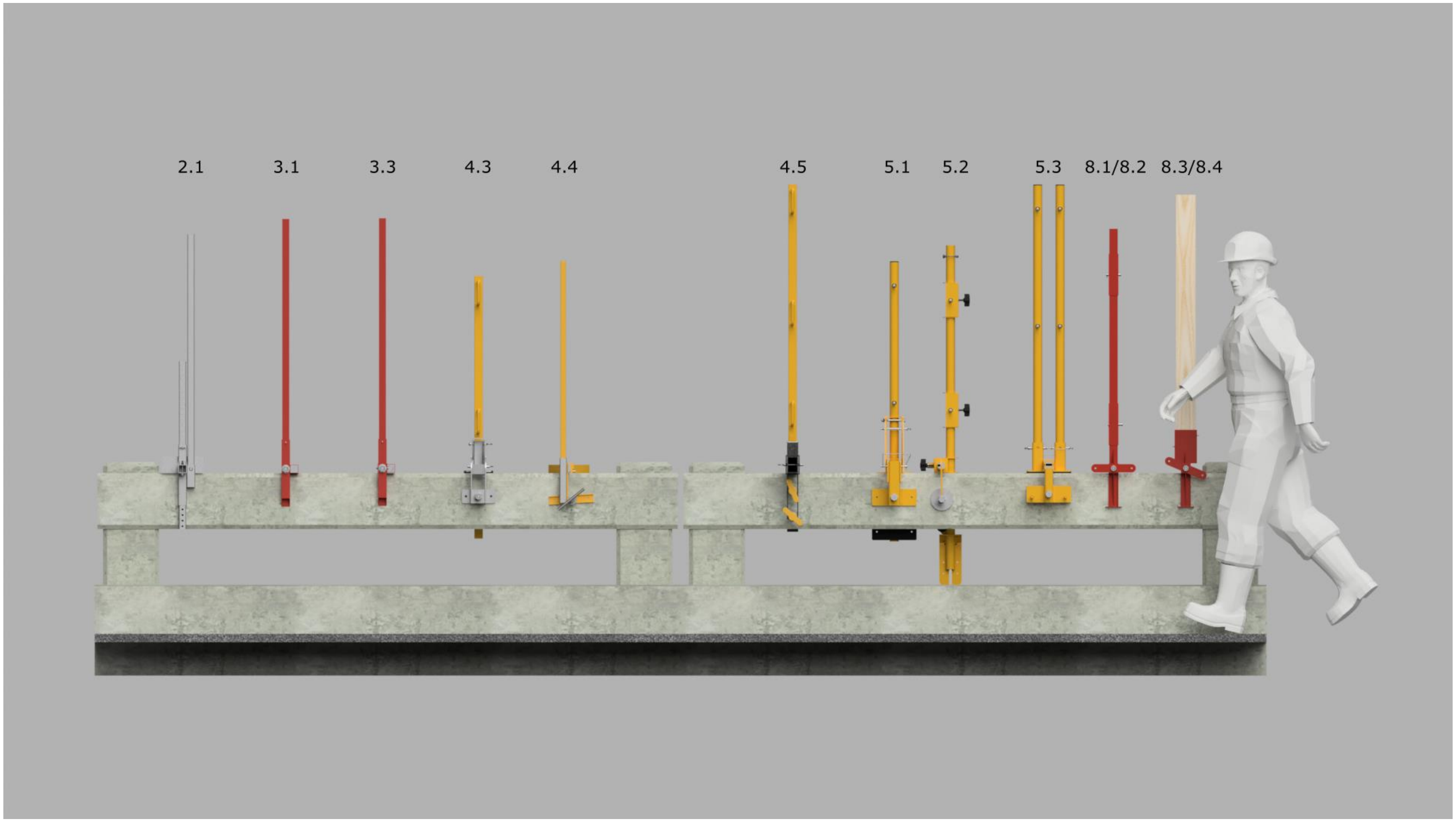


Figure 39 – Guardrail Type 11; view from the east

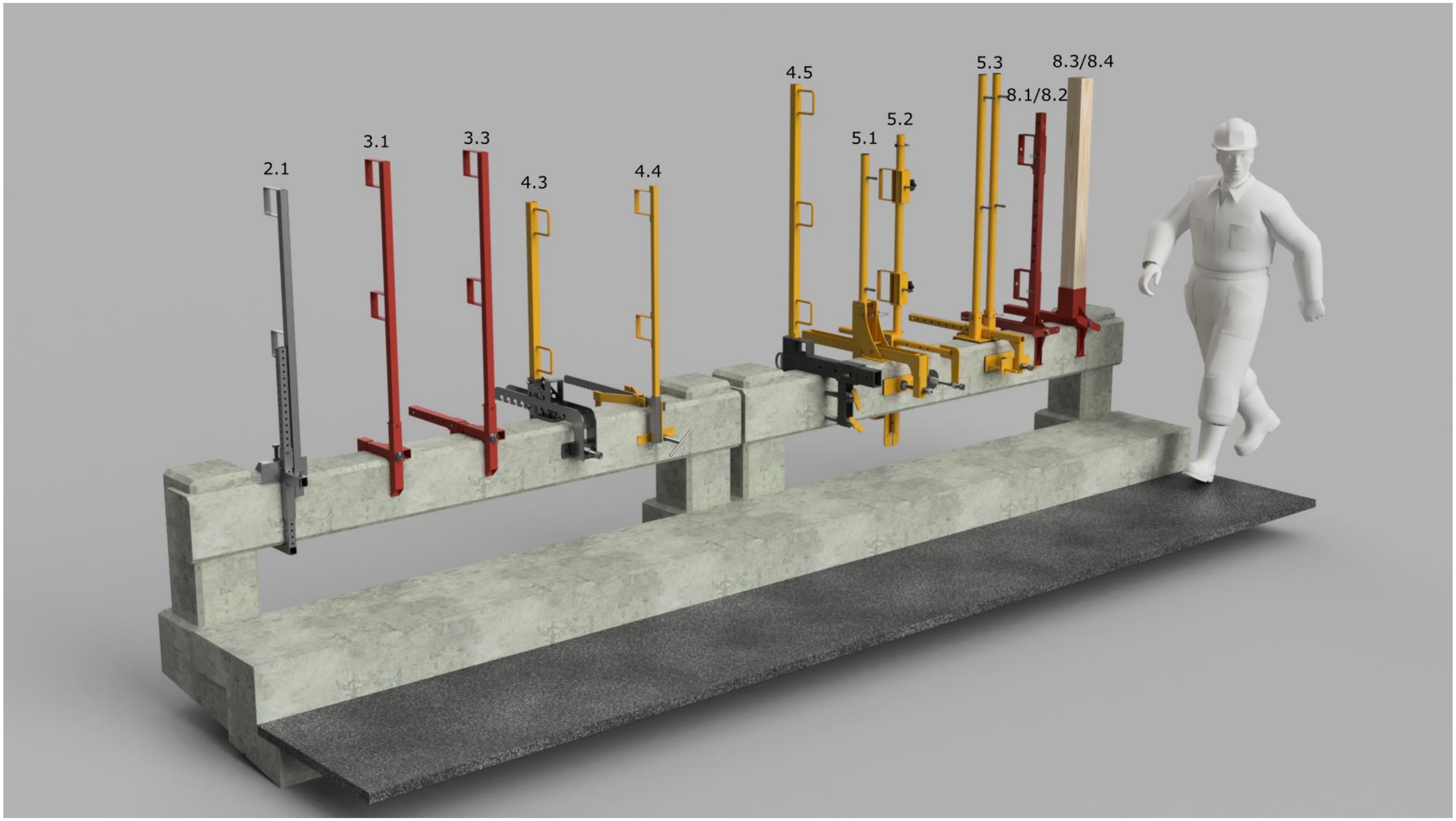


Figure 40 – Guardrail Type 11; view from the southeast

Figure 41 – Guardrail Type 11; view from the south

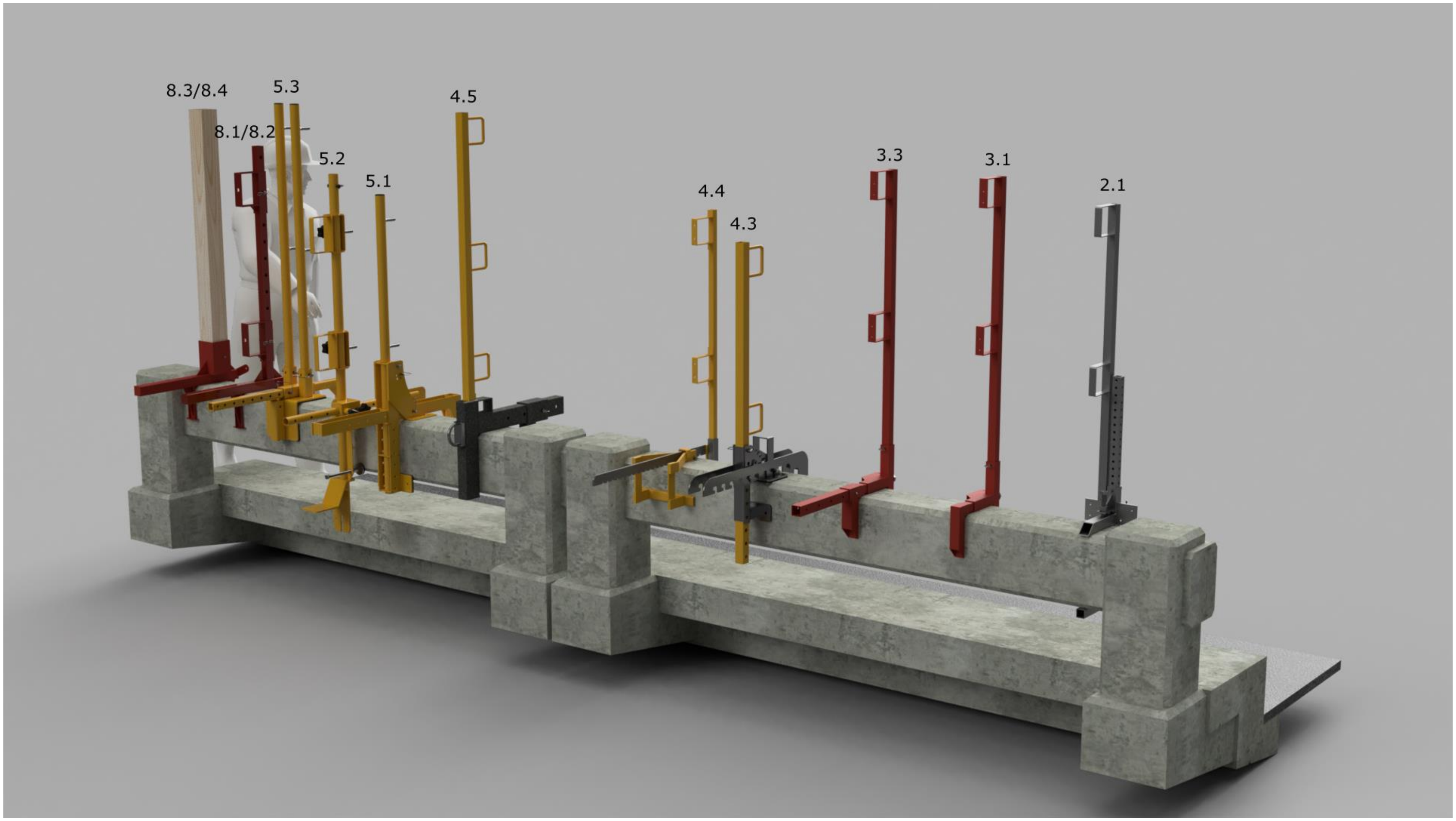


Figure 42 – Guardrail Type 11; view from the southwest

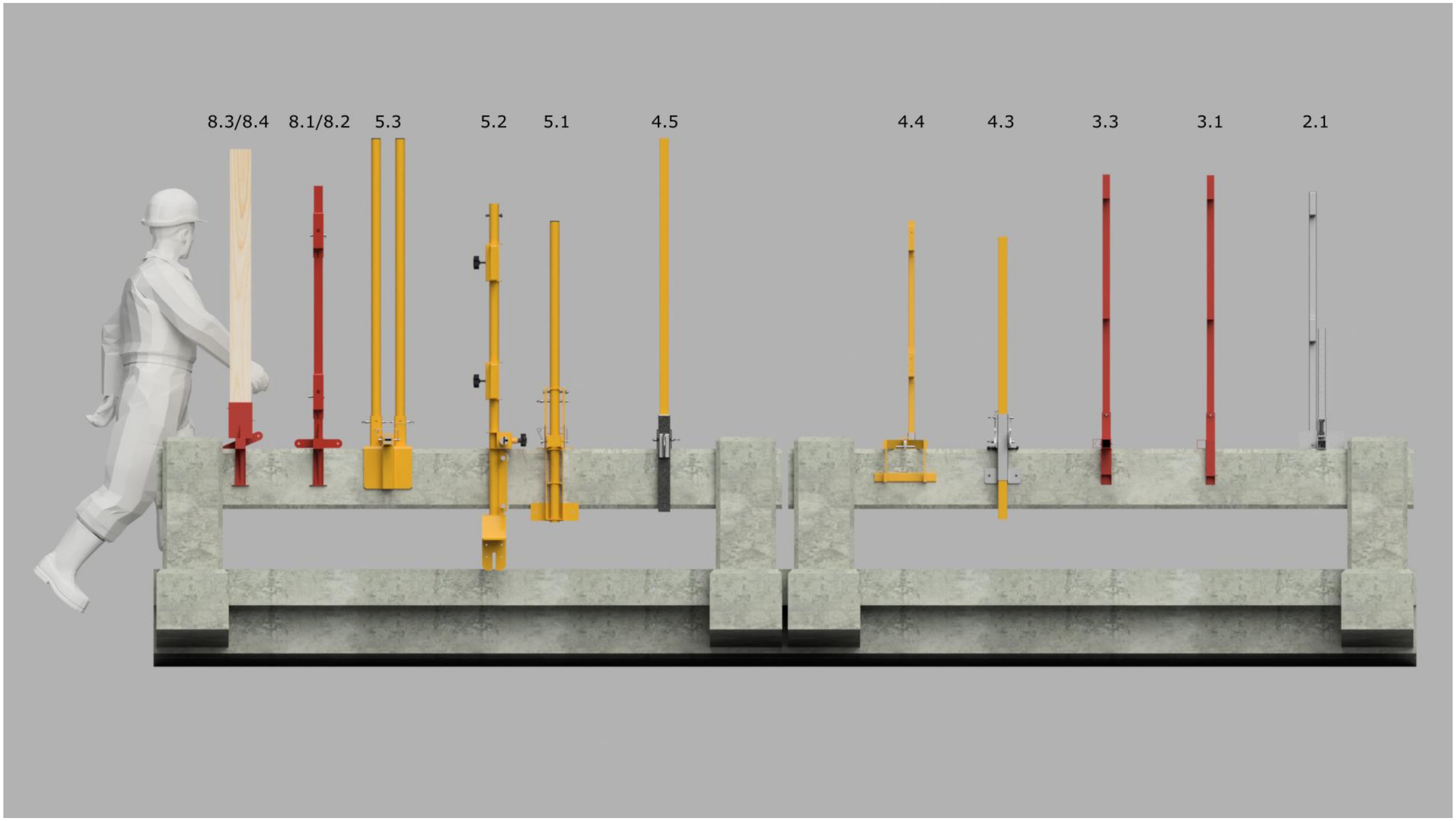


Figure 43 – Guardrail Type 11; view from the west

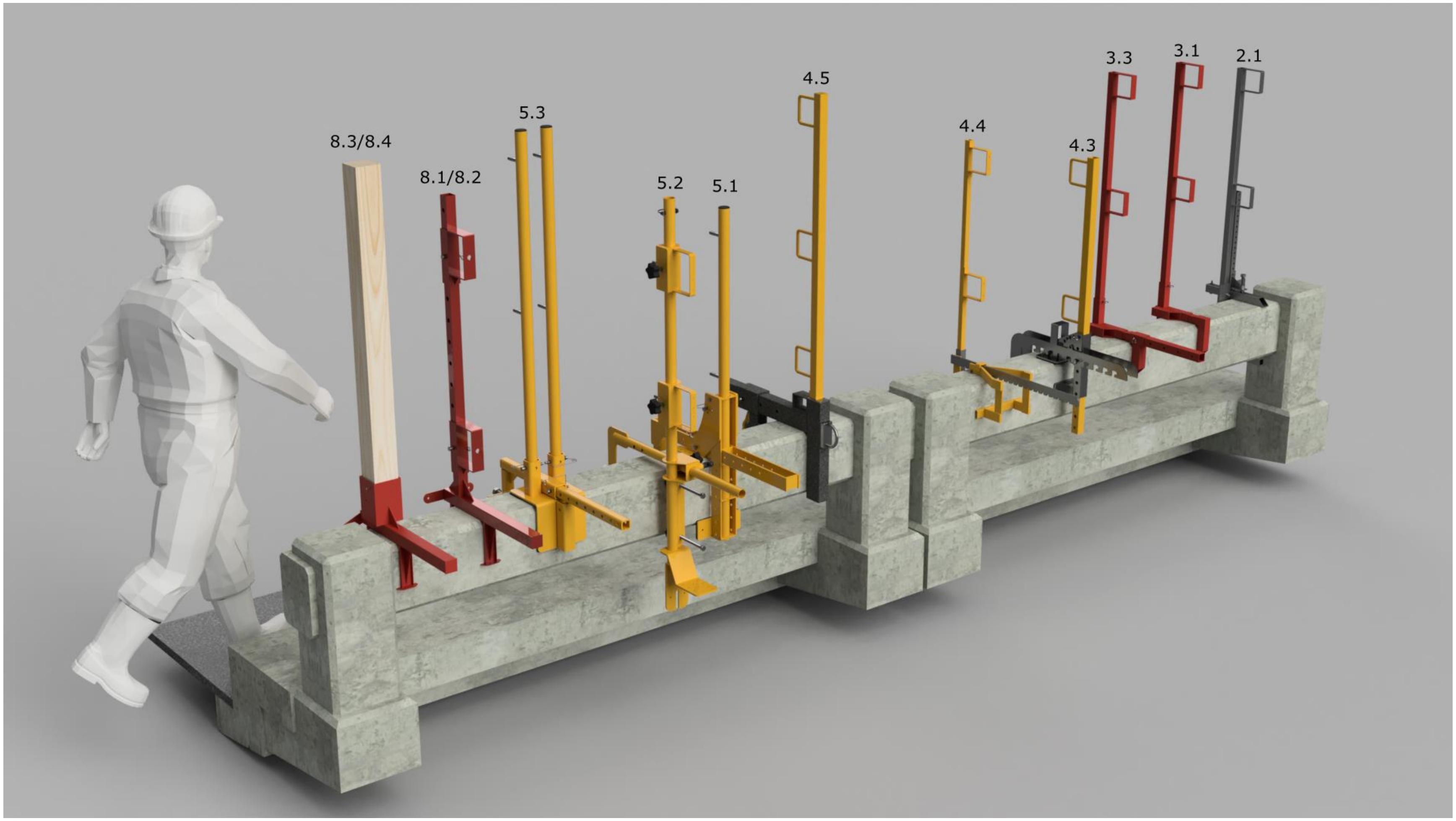


Figure 44 – Guardrail Type 11; view from the northwest

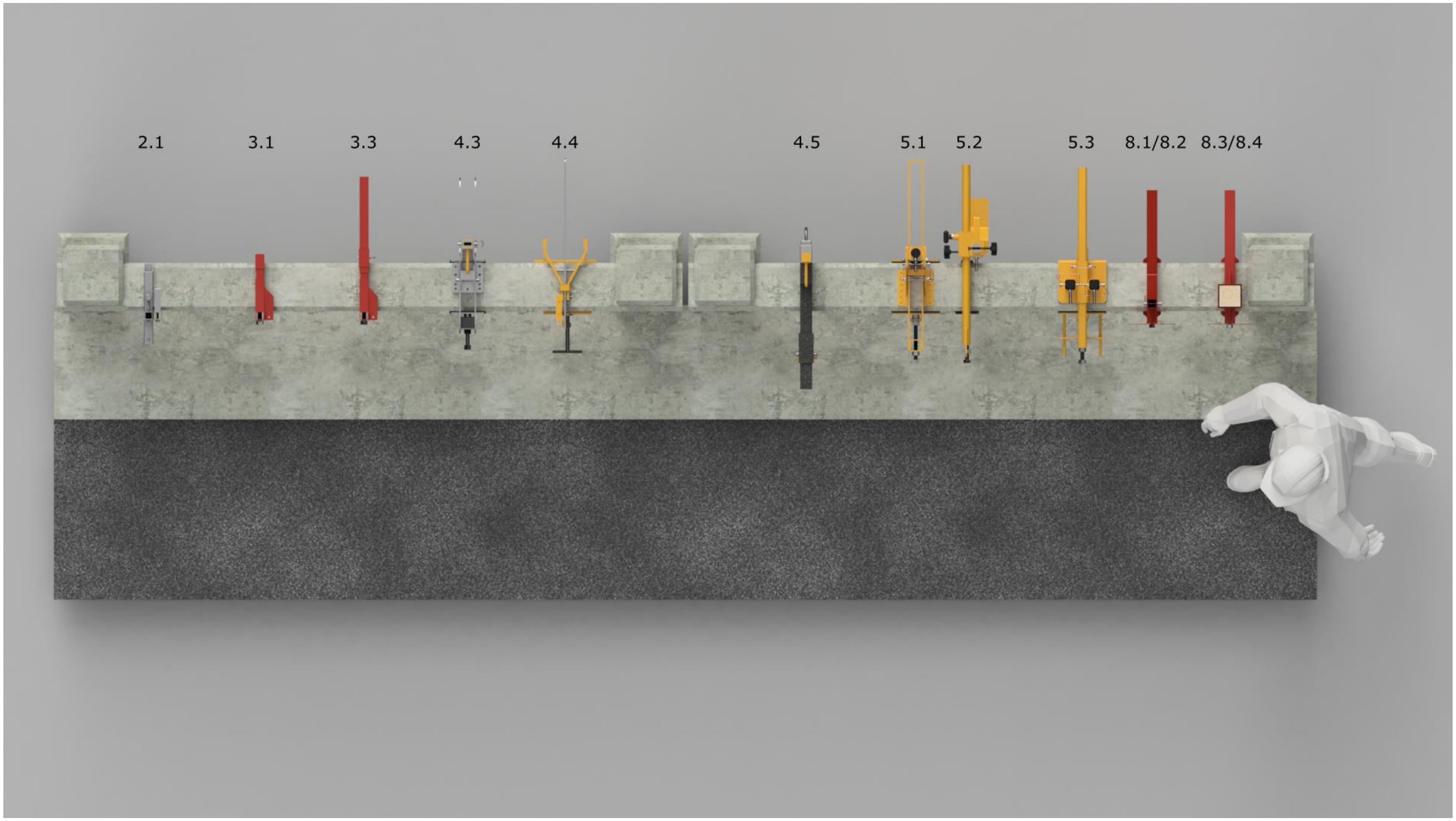


Figure 45 – Guardrail Type 11; view from the top

8. GUARDRAIL TYPE 14 – 1-Bar Concrete Rail (Middle)

8.1 Description

Concrete guardrail sections comprised of one reinforced concrete railing embedded at mid-height into two reinforced concrete supports, one at each end. After inspection of the Wiggins database, two variations of this guardrail designation were found as follows:

8.1.1 Guardrail Type 14, Variation 1

The concrete posts and mid-height bar are equal to GUARDRAIL TYPE 11 – 1-Bar Concrete Rail (Middle). As a result, the same compatible FPSD found for Guardrail Type 11 are compatible with Guardrail Type 14, variation 1. The difference between Type 11 and Type 14, variation 1 are the type of post support and the width of the curb adjacent to the guardrail. However, these characteristics do not affect the compatibility of the devices. A section is shown in Figure 46.

8.1.2 Guardrail Type 12, Variation 2

In comparison with variation 1, variation 2 dimension vary in the concrete bar (width and height are smaller by 1"), height of the post (1" higher), and dimensions of the post support. The latter is most important because there is a noticeable gap between the bridge structure and the guardrail, increasing the fall hazard for the workers, consequently increasing the difficulty to install the compatible FPSDs. A section is shown on

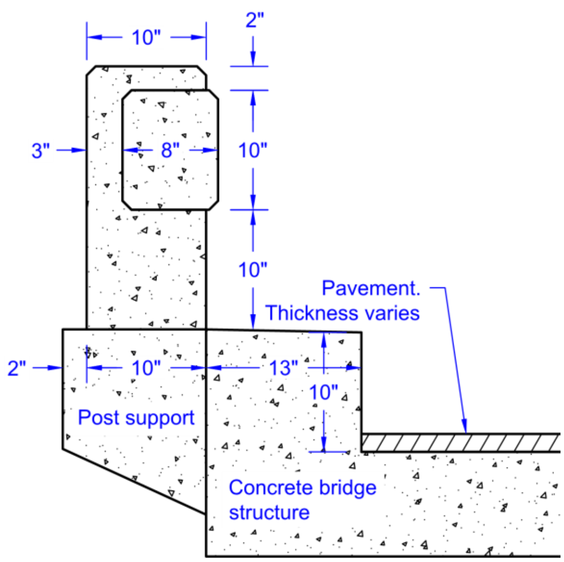


Figure 46 – Guardrail Type 14, variation 1 section

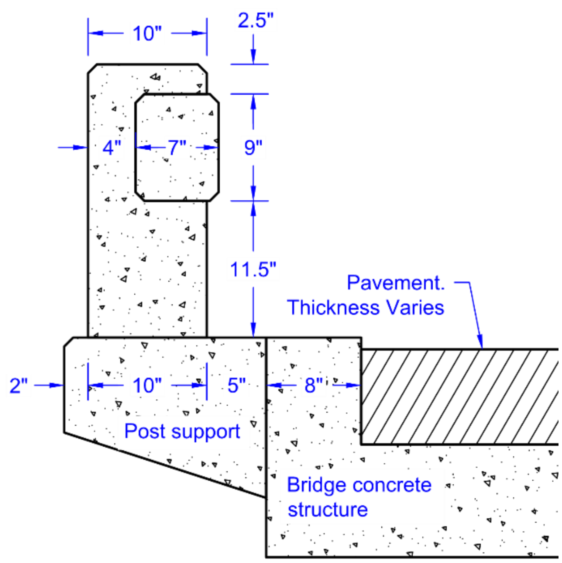


Figure 47 – Guardrail Type 14, variation 2 section

14

8.2 Compatibility Chart

The following is the compatibility chart for Guardrail Type 12, variation 2. For variation 1, refer to GUARDRAIL TYPE 11 – 1-Bar Concrete Rail (Middle).

Table 7 – Compatibility chart for Guardrail Type 14, Variation 2

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as slab clamp as it intrudes the least into the work area. There is no intrusion into the work area. Protrusion from the guardrail is approximately 5.5”.
3.1	C-Clamp - CC120	The device fits over the rail as either slab clamp or parapet clamp. Because the width of the concrete bar is the same as the minimum opening of the device, it is advisable to use it as a slab clamp until validation studies are performed. Model is shown as slab clamp with no intrusion into the work area. Protrusion from the guardrail is 6” as it intrudes the least into the work area (approximately 2.25”).
3.3	Master C-Clamp - MCC130	This device fits over the concrete rail as slab clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 6”.
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 6.5”.
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 6.75”.
4.5	Parapet Anchor - 15171	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 14”.
5.1	RaptorRail	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 8.75”.
5.2	All-In-One	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 8.75”.
5.3	Universal Guardrail Parapet Clamp	The device fits over the rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as it offers the most convenient and safest installation. There is no intrusion into the work area. Protrusion from the guardrail is approximately 8.75”.
8.1	Parapet Guardrails GRS-P12	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 2.75”
8.2	Parapet Guardrails GRS-P24	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 2.75”
8.3	QuickRail Parapet Guardrail QR-P12	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 2.75”
8.4	QuickRail Parapet Guardrail QR-P24	This device fits over the concrete rail as parapet clamp. There is no intrusion into the work area. Protrusion from the guardrail is approximately 2.75”

8.3 Renderings

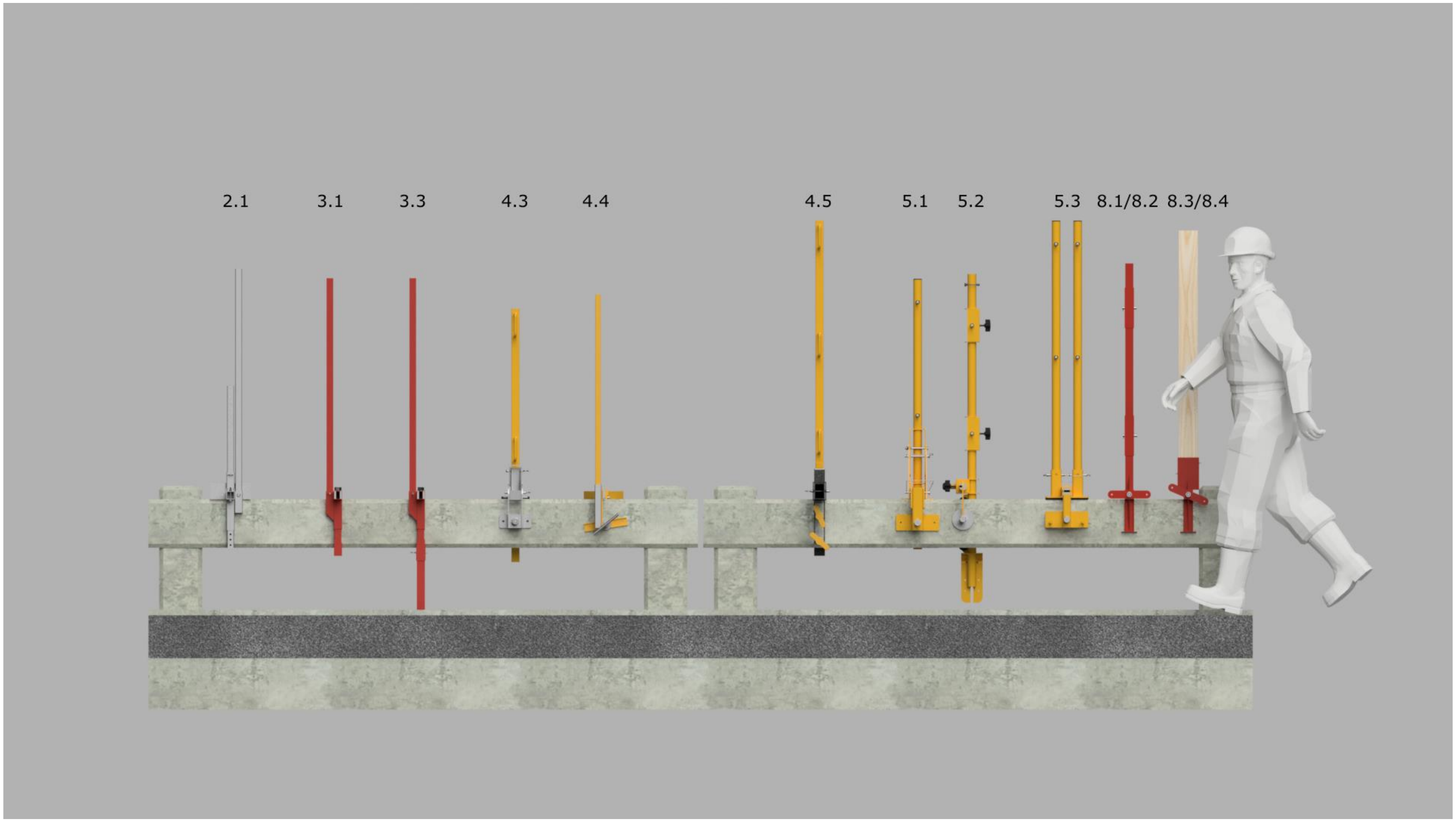


Figure 48 – Guardrail Type 14, variation 2; view from the east

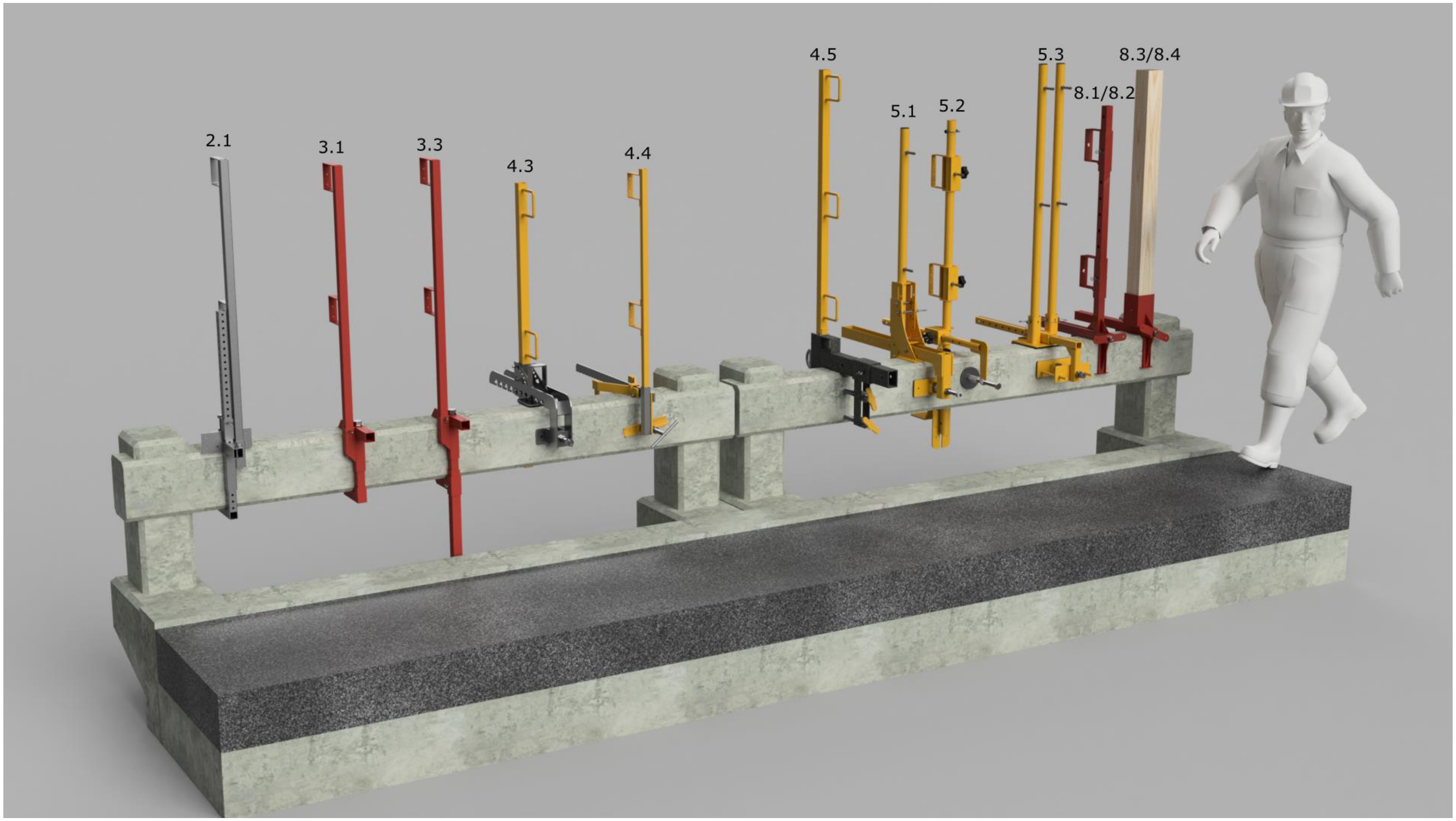


Figure 49 – Guardrail Type 14, variation 2; view from the southeast


Figure 50 – Guardrail Type 14, variation 2; view from the south

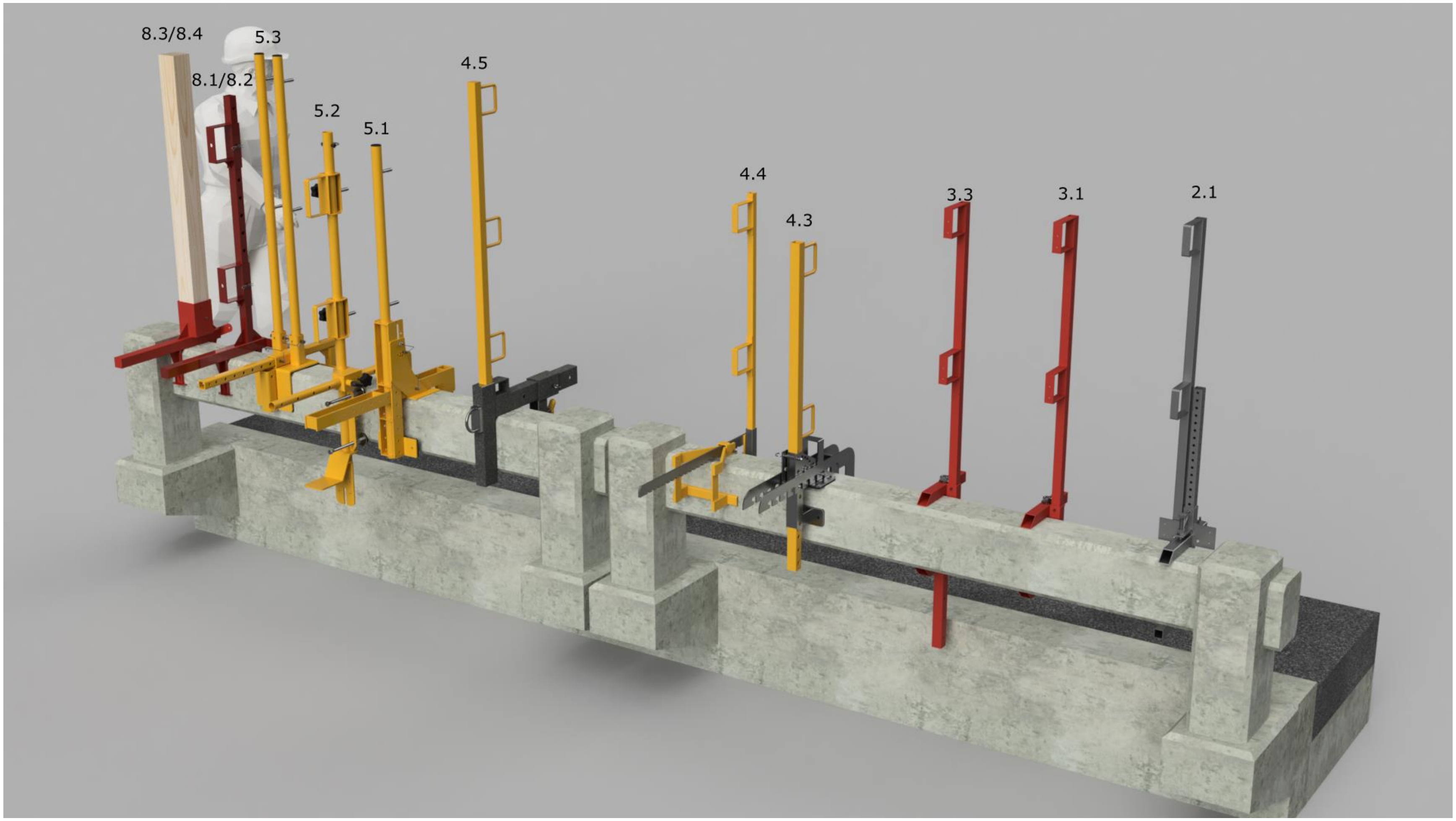


Figure 51 – Guardrail Type 14, variation 2; view from the southwest

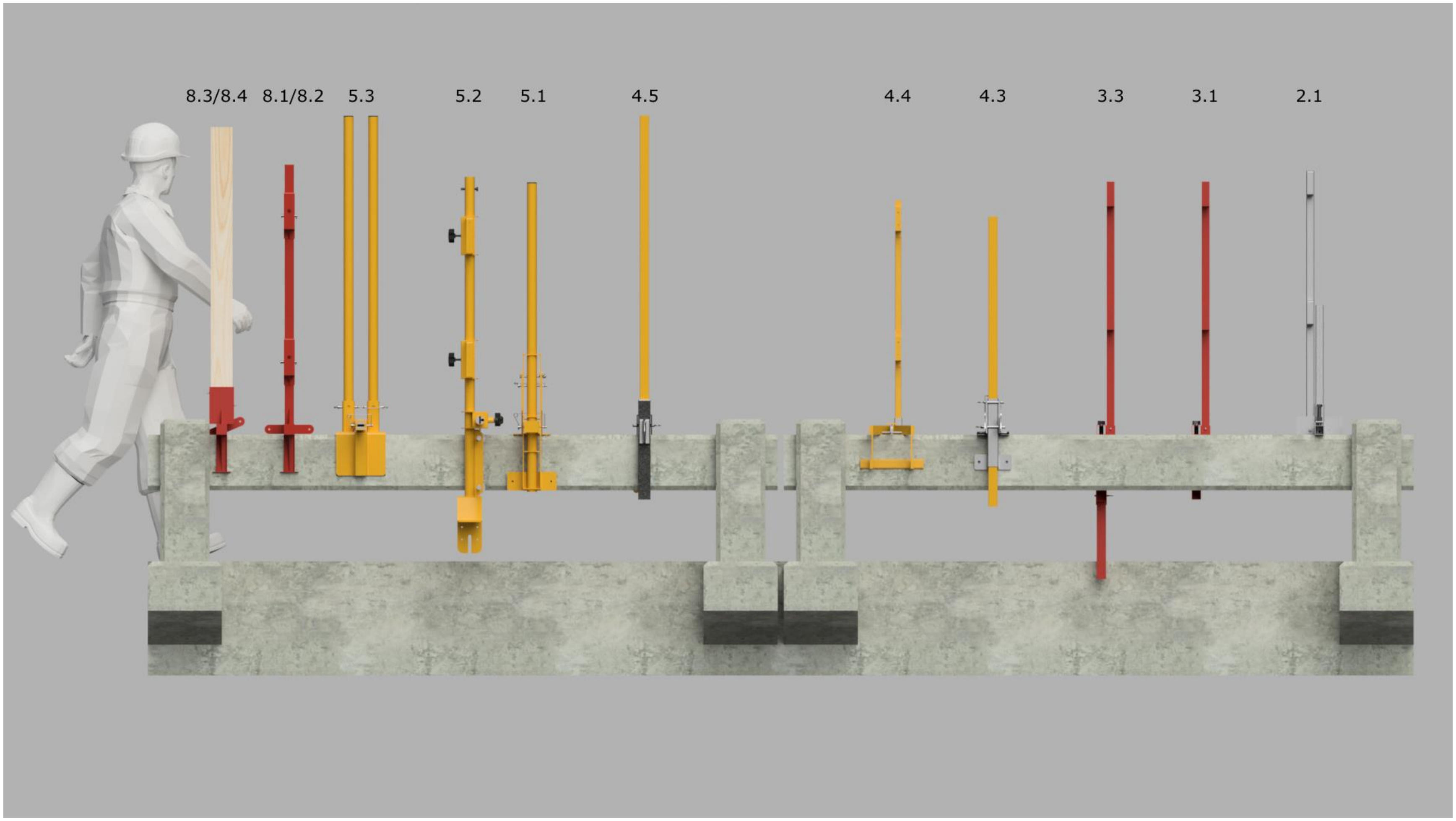


Figure 52 – Guardrail Type 14, variation 2; view from the west

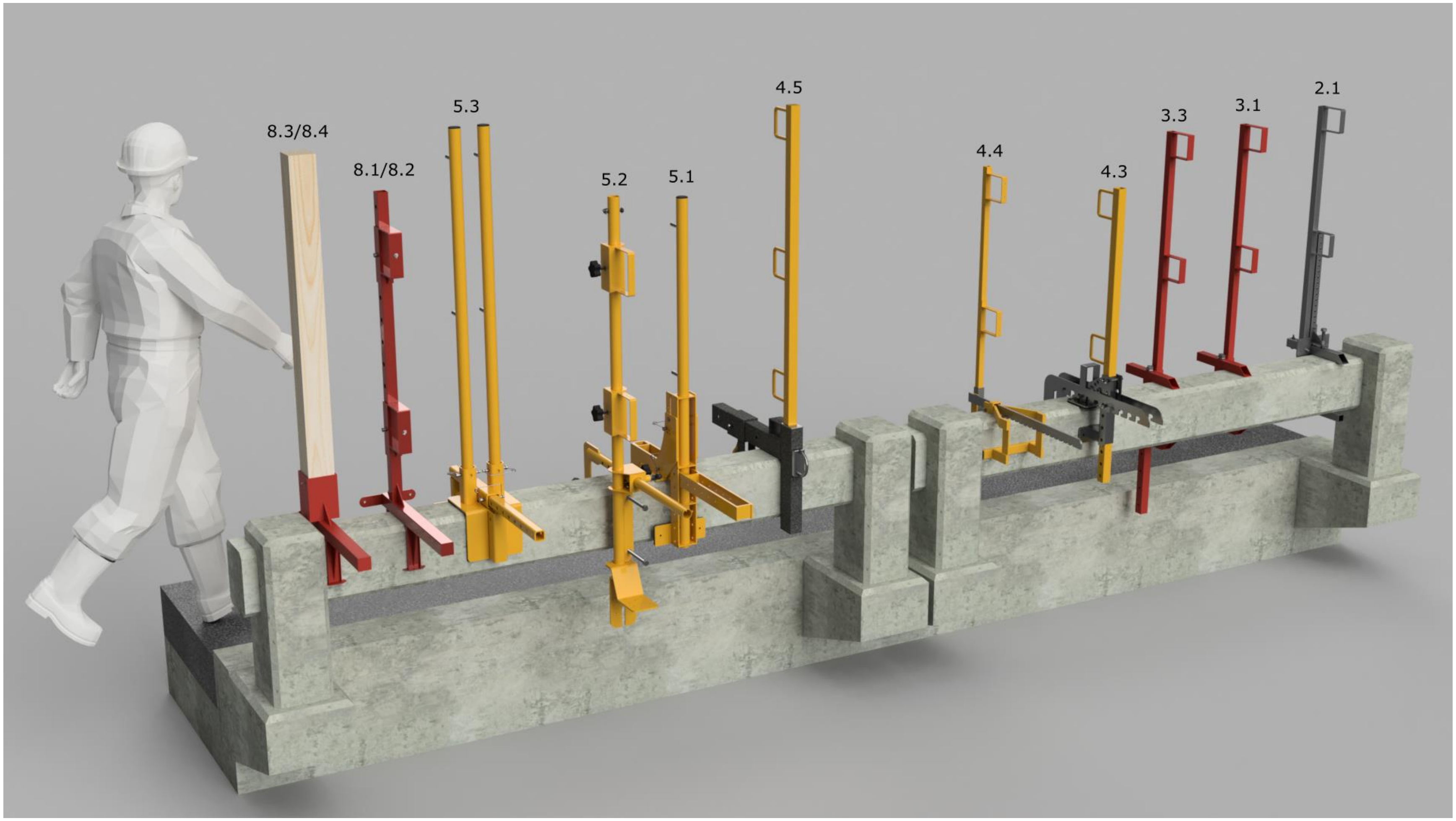


Figure 53 – Guardrail Type 14, variation 2; view from the northwest

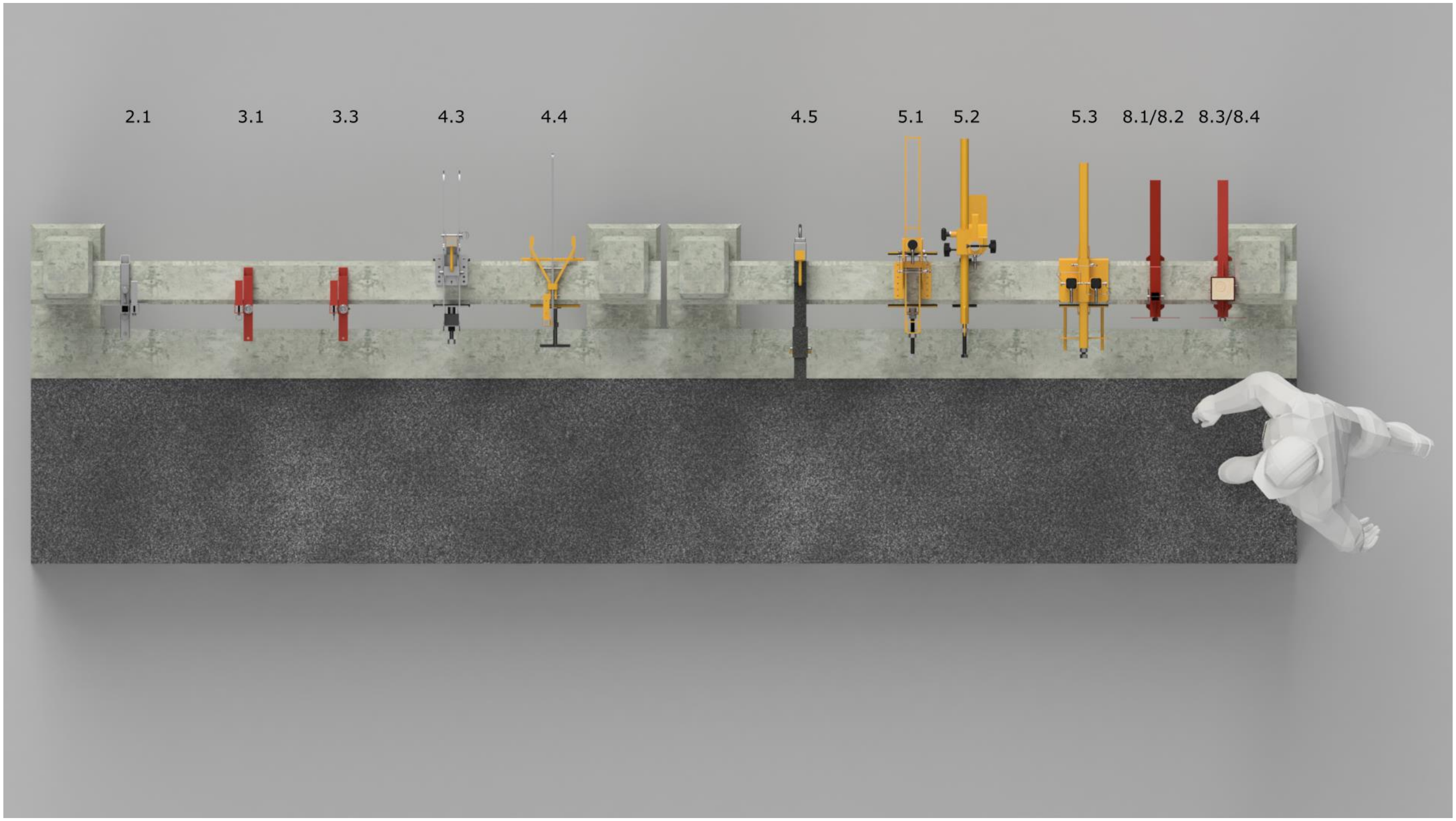


Figure 54 – Guardrail Type 14, variation 2; view from the top

9. GUARDRAIL TYPE 22 – Wood Guardrail

9.1 Description

Guardrail type constructed mainly of dimensional lumber. It is comprised of a wheel guard close to the working surface, 4"x6" posts supporting one 2"x6" mid rail, and a two perpendicular 2"x6" planks as top rail.

We considered two possible scenarios for securing the FPSD to the guardrail. First, attaching the FPSDs to the top rail. Second, attaching the FPSDs to the 6"x8" wheel guard. In the compatibility chart, there will be statements regarding the minimum size of wood blocks required for proper fitting of the FPSD. When only a 4"W piece is required, the FPSD can be directly attached to the rail post and this would fulfill the need for a block. If a thicker piece is needed, and placement is possible at the rail post, then subtract the 4" width of the rail post. Otherwise, use the specified woodblock.

In the first fitment option, we considered that top plank laid horizontally as top rail, would not be able to support the forces applied by the FPSD. Therefore, wood blocks are recommended to spread the load between the two 2"x6" planks of the top rail, also minimizing the damage to the guardrail due to the clamping pressure from the FPSD.

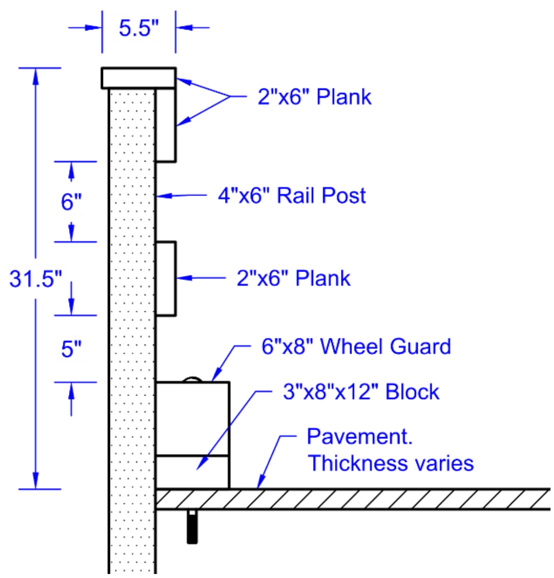


Figure 55 - Guardrail Type 22 section

9.2 Compatibility Chart

Table 8 - Compatibility chart for Guardrail Type 22

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	**Guardrail**: The device fits over the top of the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. Intrusion into the work area is approximately 19". **Wheel Guard:** This device **does not fit** on the wheel guard. The device will not close enough to clamp the wheel guard.
3.1	C-Clamp - CC120	**Guardrail:** The device fits over the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. There is no intrusion into the work area.

ID	PRODUCT NAME	COMPATIBILITY NOTES
		Wheel Guard: This device **does not fit** on the wheel guard. The device will not close enough to clamp the wheel guard.
3.3	Master C-Clamp - MCC130	**Guardrail:** This device fits over the guardrail. An 8"W x 6"L lumber piece in the back of the guardrail is needed. There is no intrusion into the work area. **Wheel Guard:** This device **does not fit** on the wheel guard. There is interference between the device and the mid rail.
4.3	Alligator Parapet Guardrail system - 15167	**Guardrail:** This device fits over the guardrail. A 4"W x 6"L lumber piece in the back of the guardrail is needed. Intrusion into the work area is approximately 2.5". **Wheel Guard:** This device **does not fit** over the wheel guard. There is interference between the device and the mid rail.
4.4	Parapet Clamp Guardrail System - 15170	**Guardrail:** This device fits over the guardrail. A 4"W x 6"L lumber piece in the back of the guardrail is needed. Intrusion into the work area is approximately 3". **Wheel Guard:** This device fits over the wheel guard. Intrusion into the work area is approximately 7".
4.5	Parapet Anchor - 15171	**Guardrail:** This device fits over the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. It is believed that the aged and weathered lumber may get damaged by the pressure of the tightening bolts. Intrusion into the work area is approximately 4". **Wheel Guard:** This device **does not fit** on the wheel guard. There is interference between the device and the mid rail.
5.1	RaptorRail	**Guardrail:** This device fits over the guardrail. A 4"W x 6"L lumber piece in the back of the guardrail is needed. Intrusion into the work area is approximately 4.75". **Wheel Guard:** This device **does not fit** on the wheel guard. There is interference between the device and the mid rail.
5.2	All-In-One	**Guardrail:** This device fits over the guardrail. A 2"W x 12"L lumber piece in the back of the guardrail is needed. Intrusion into the work area is approximately 4.75". **Wheel Guard:** This device **does not fit** on the wheel guard. There is interference between the device and the mid rail.
5.3	Universal Guardrail Parapet Clamp	**Guardrail:** This device fits over the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. Intrusion into the work area is approximately 4.75". **Wheel Guard:** This device fits over the wheel guard. Tightening bolt faces the inside of the bridge. Intrusion into the work area is approximately 8.75".
8.1	Parapet Guardrails GRS-P12	**Guardrail:** This device fits over the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. There is no intrusion into the work area. **Wheel Guard:** Device fits over the wheel guard. Tightening handle faces the inside of the bridge. Intrusion into the work area is approximately 2.75".
8.2	Parapet Guardrails GRS-P24	**Guardrail:** This device fits over the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. There is no intrusion into the work area. **Wheel Guard:** Device fits over the wheel guard. Tightening handle faces the inside of the bridge. Intrusion into the work area is approximately 2.75".
8.3	QuickRail Parapet Guardrail QR-P12	**Guardrail:** This device fits over the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. There is no intrusion into the work area. **Wheel Guard:** Devices **does not fit** over the wheel guard. There is interference between the device wood post and the mid rail.
8.4	QuickRail Parapet Guardrail QR-P24	**Guardrail:** This device fits over the guardrail. A 6"W x 6"L lumber piece in the back of the guardrail is needed. There is no intrusion into the work area. **Wheel Guard:** Devices **does not fit** over the wheel guard. There is interference between the device wood post and the mid rail.

9.3 Renderings

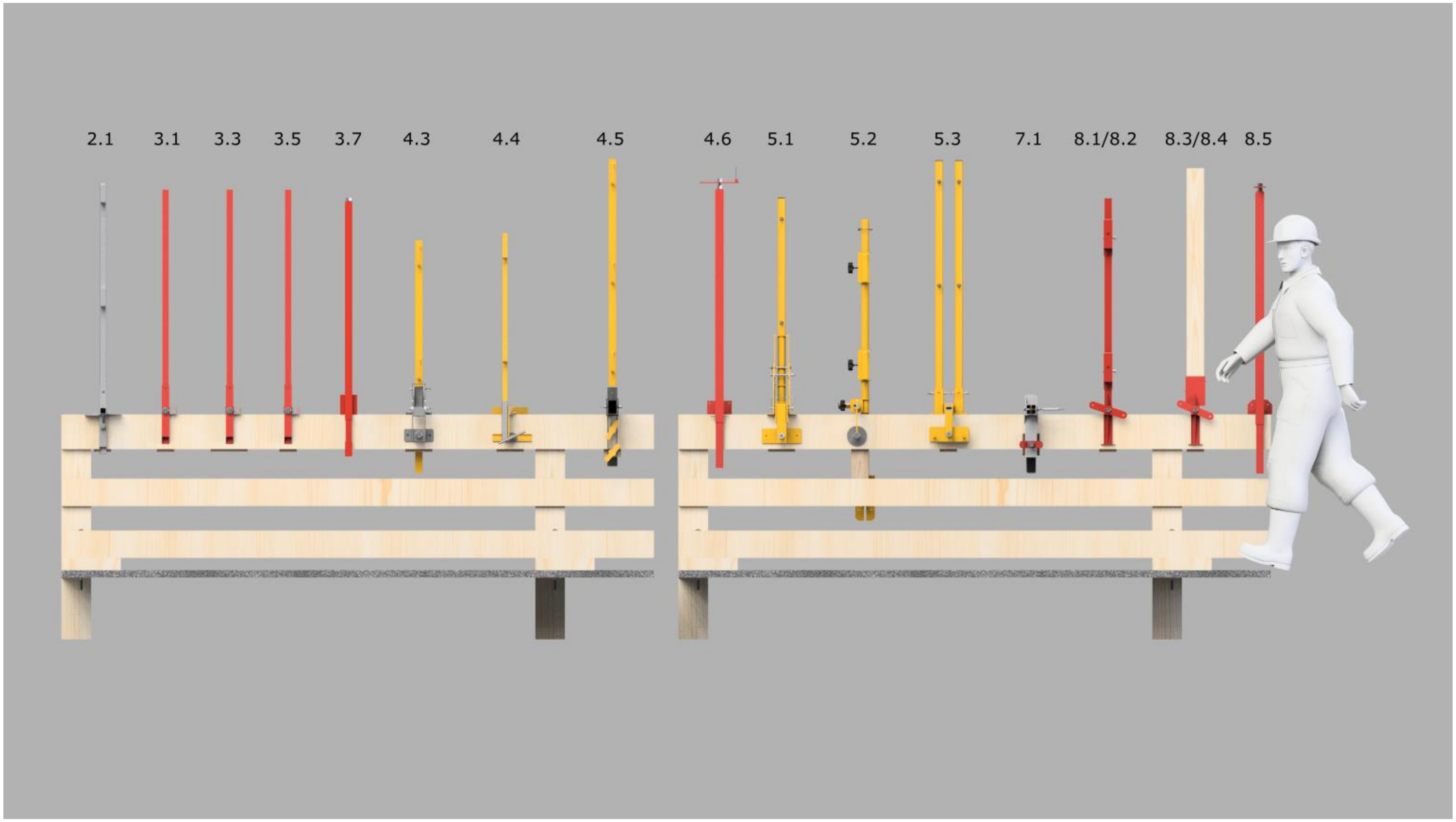


Figure 56 – Guardrail Type 22, guardrail fit; view from the east

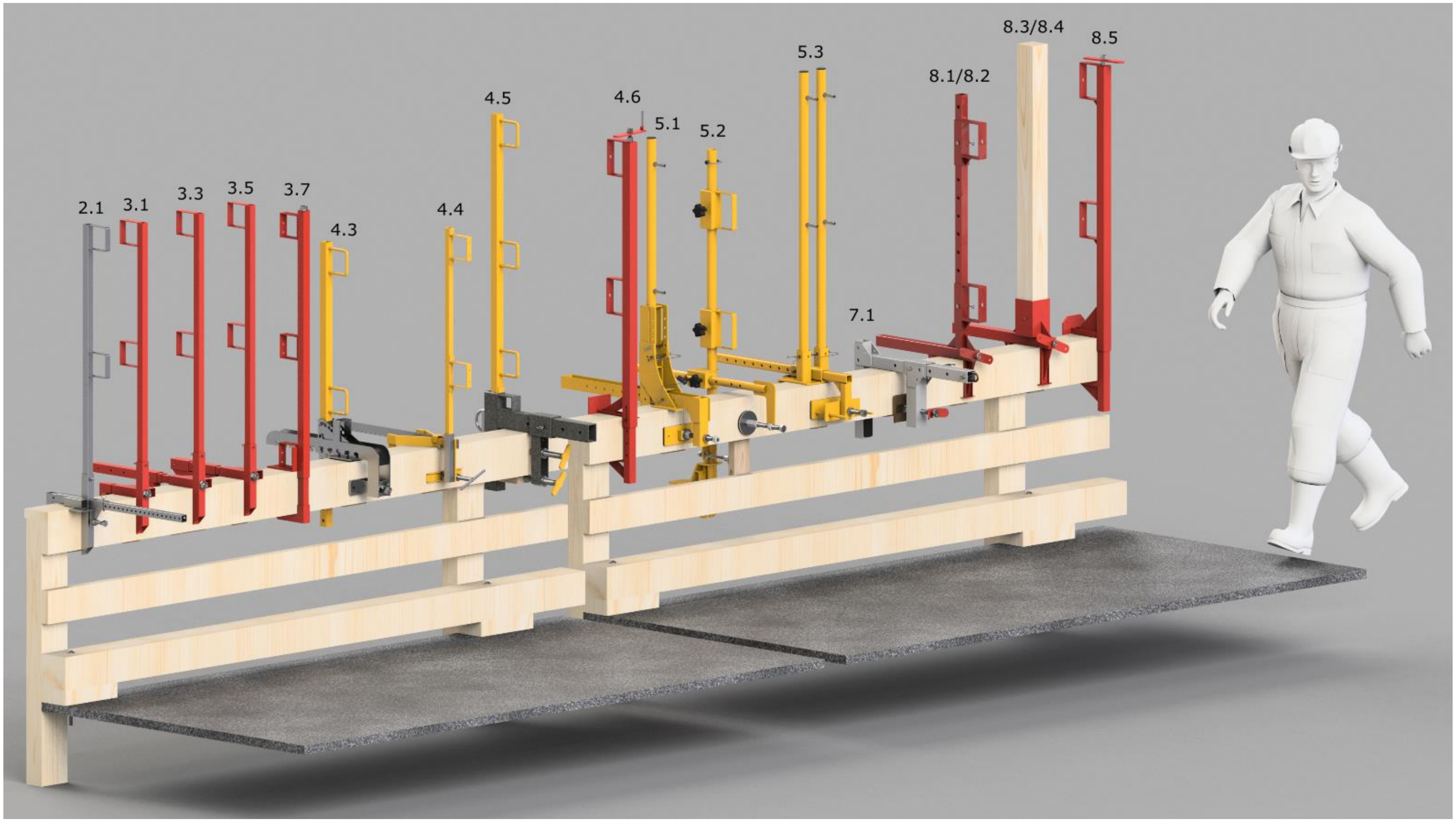


Figure 57 – Guardrail Type 22, guardrail fit; view from the southeast

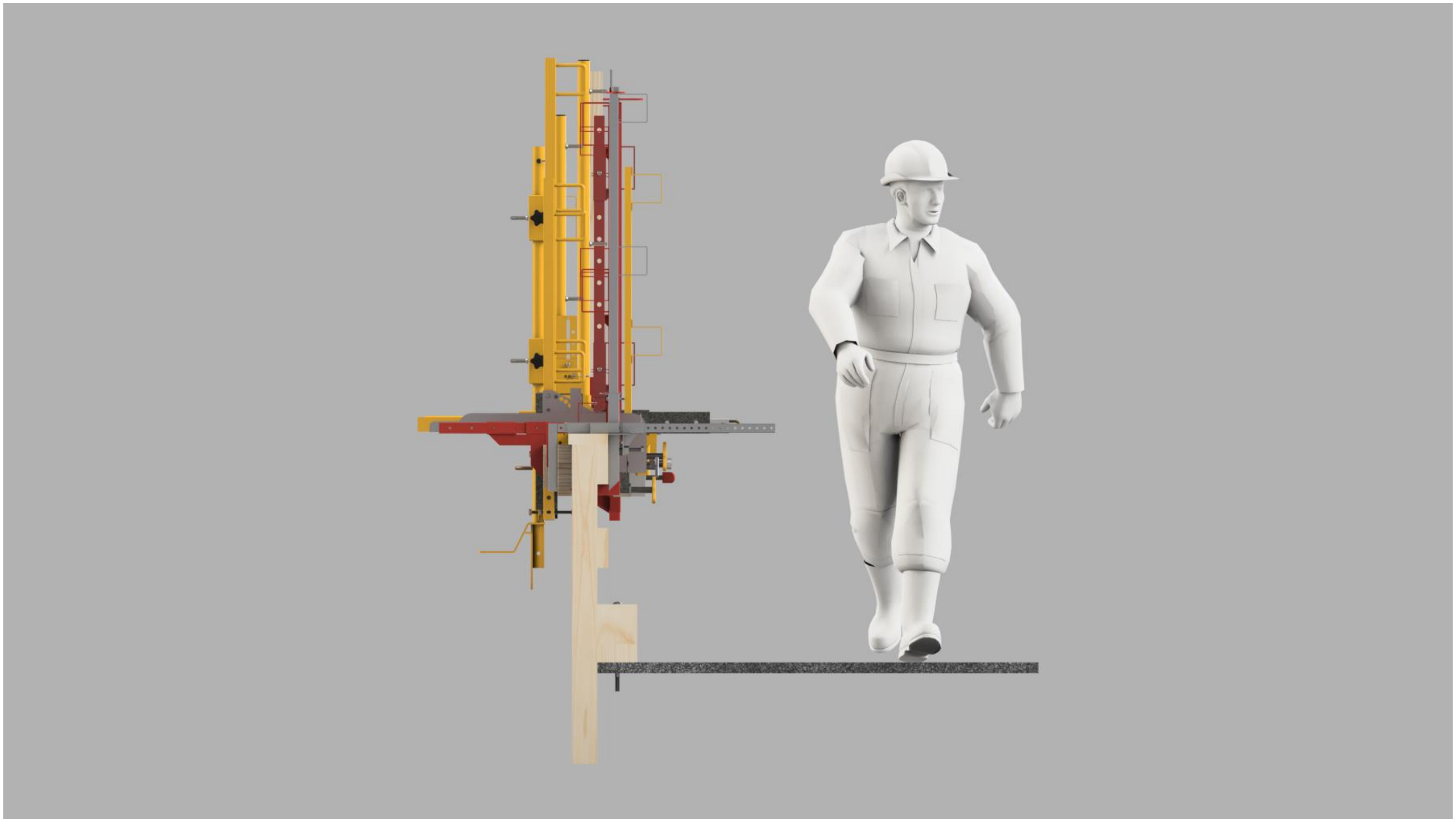


Figure 58 – Guardrail Type 22, guardrail fit; view from the south

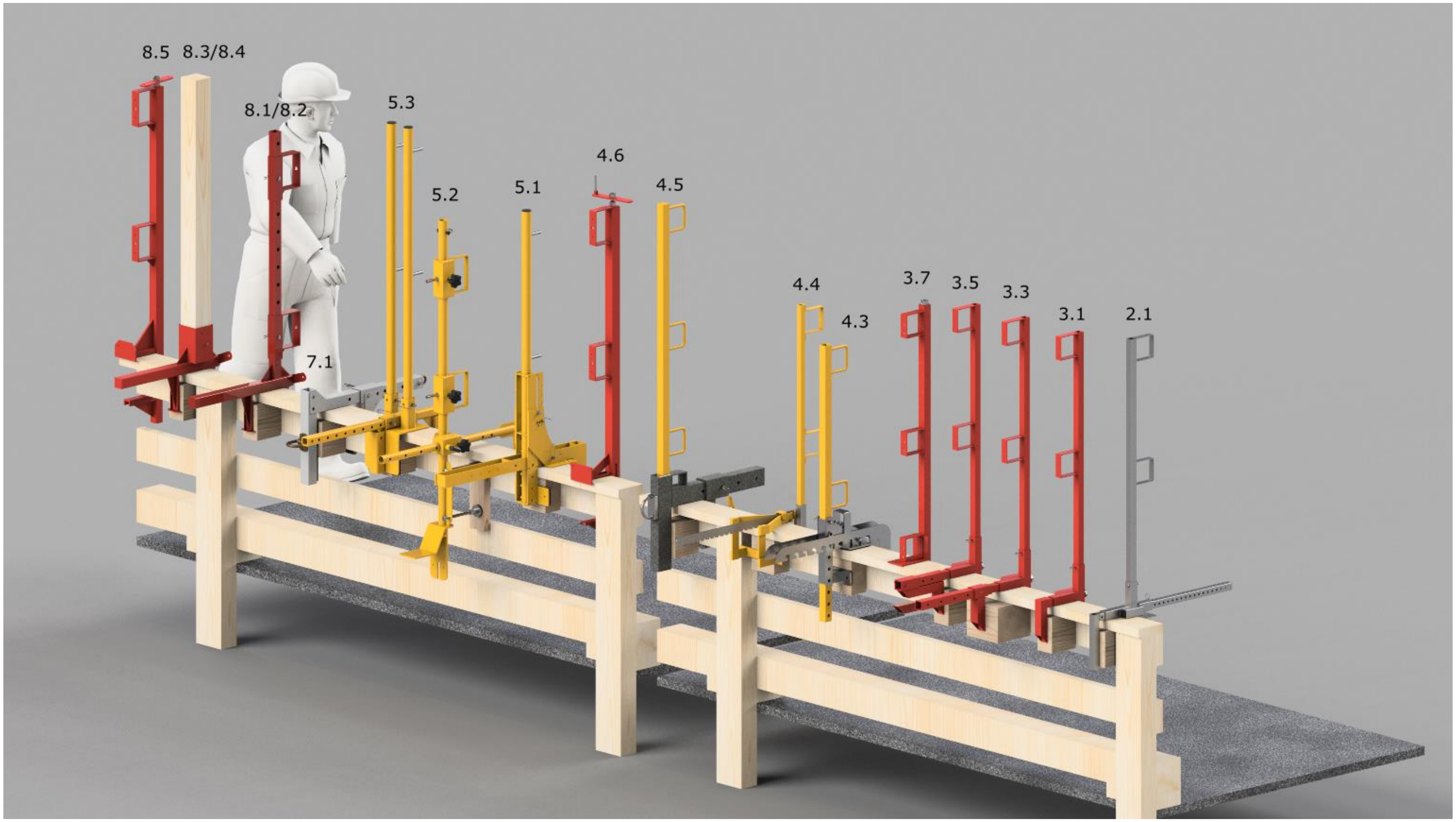


Figure 59 – Guardrail Type 22, guardrail fit; view from the southwest

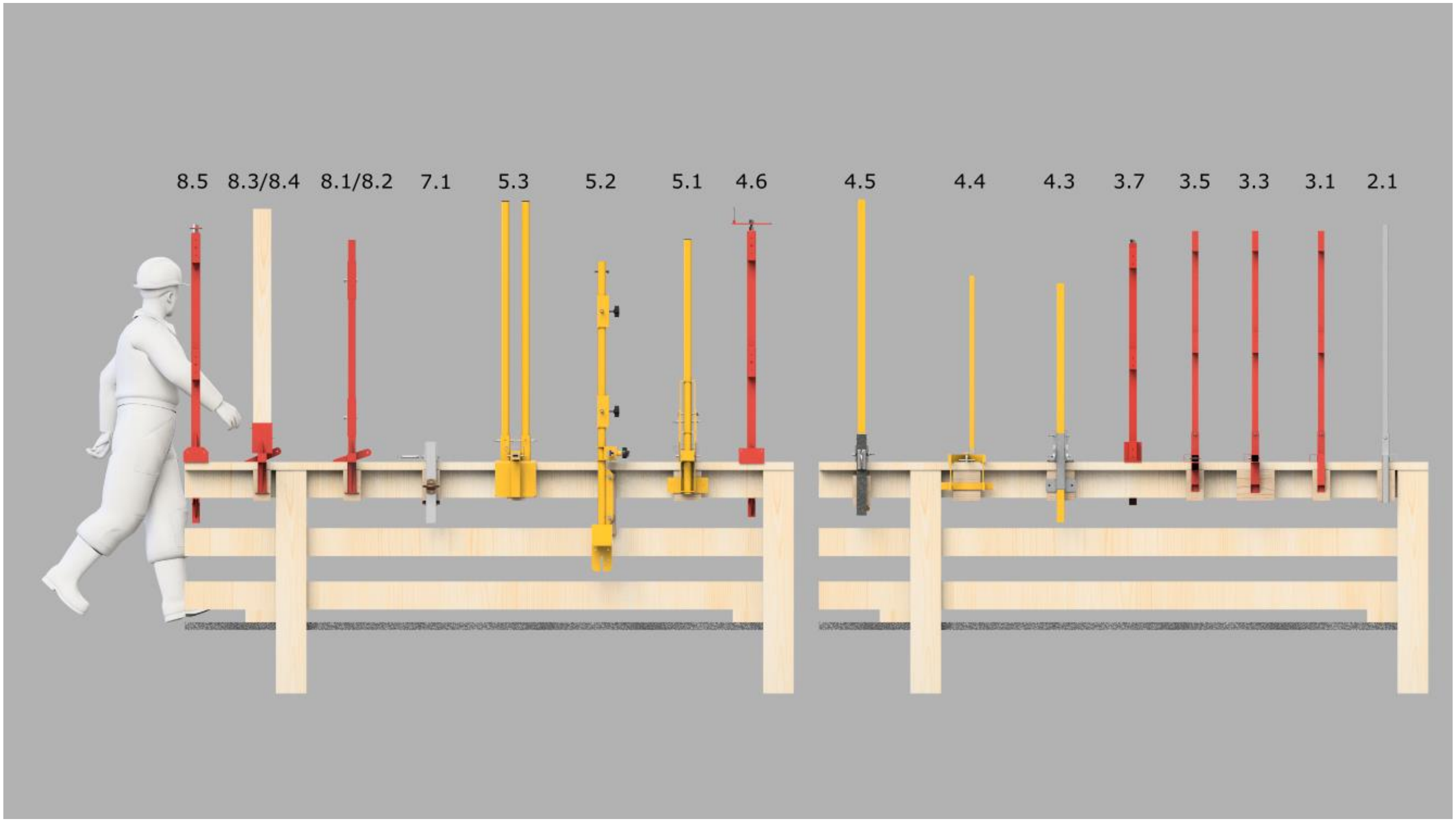


Figure 60 – Guardrail Type 22, guardrail fit; view from the west

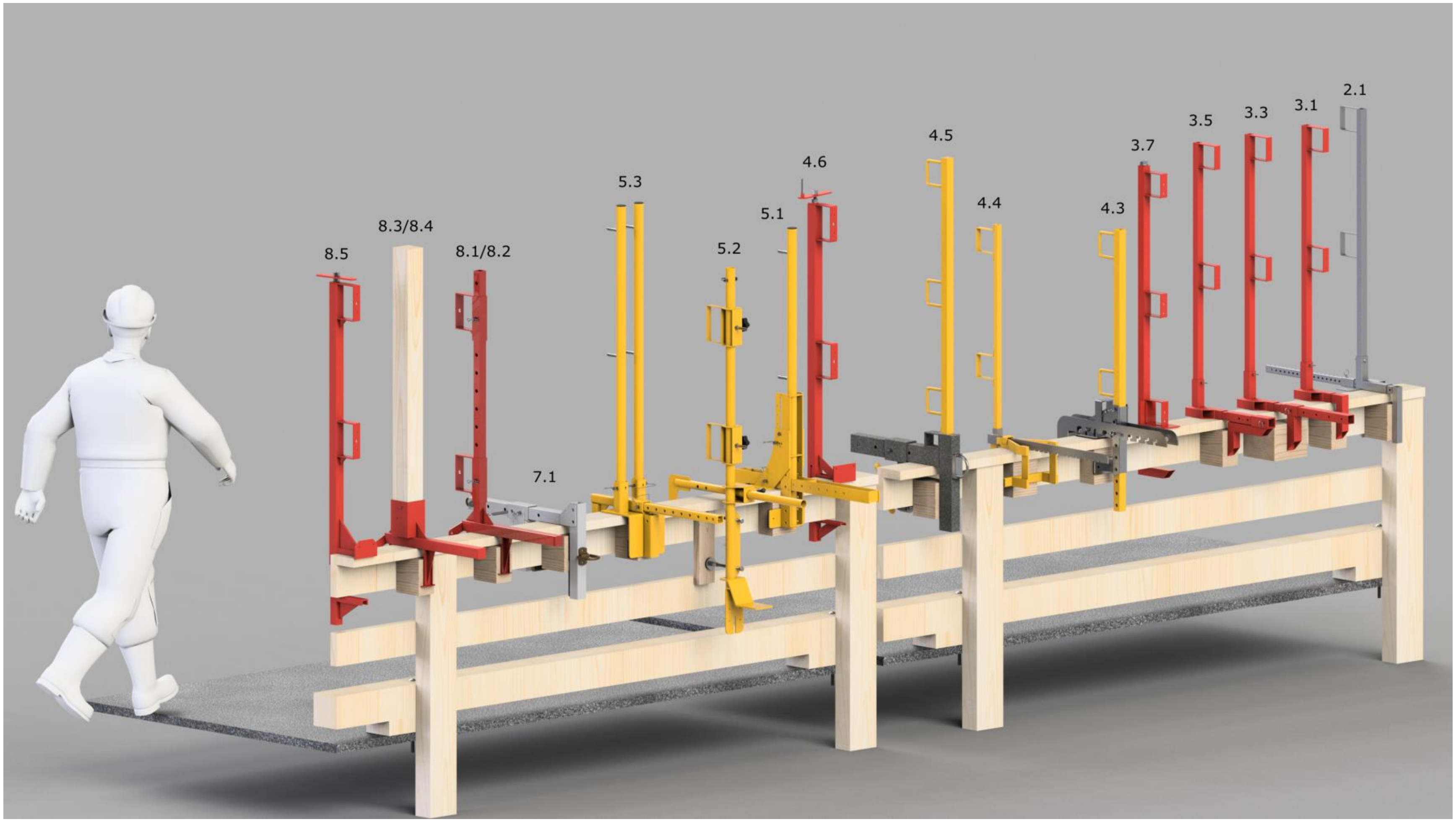


Figure 61 – Guardrail Type 22, guardrail fit; view from the northwest

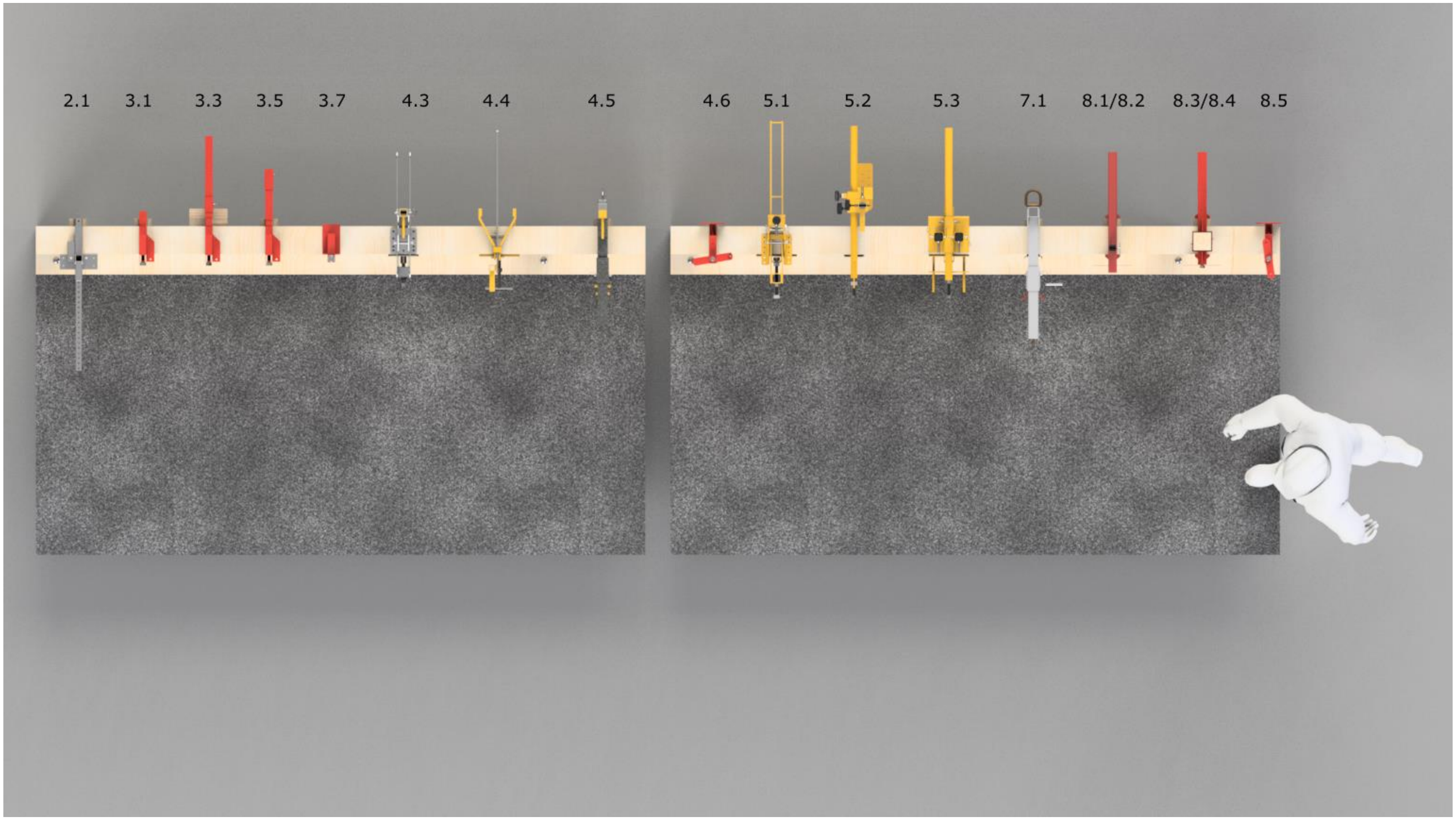


Figure 62 – Guardrail Type 22, guardrail fit; view from the top

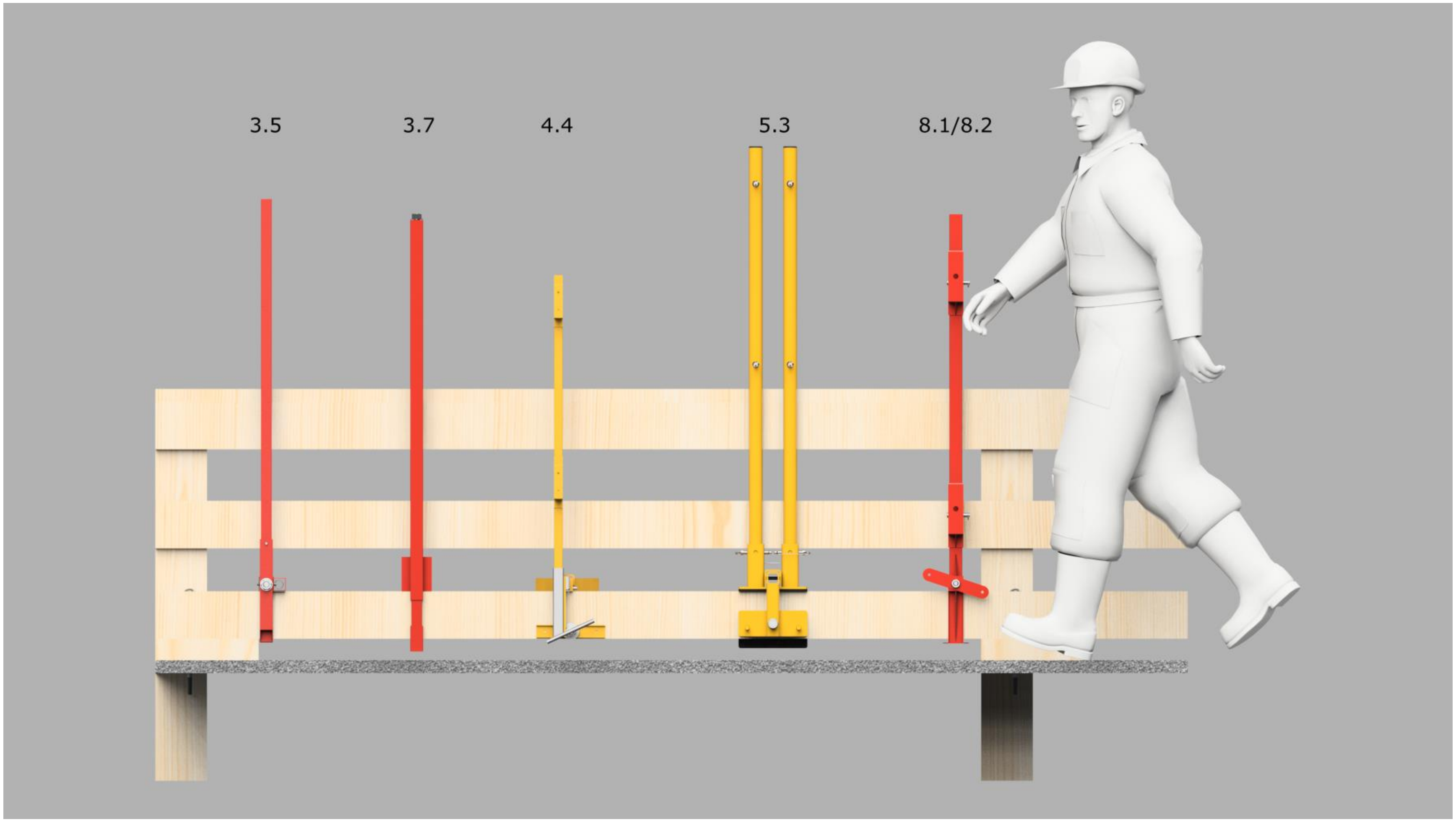


Figure 63 – Guardrail Type 22, wheel guard fit; view from the east

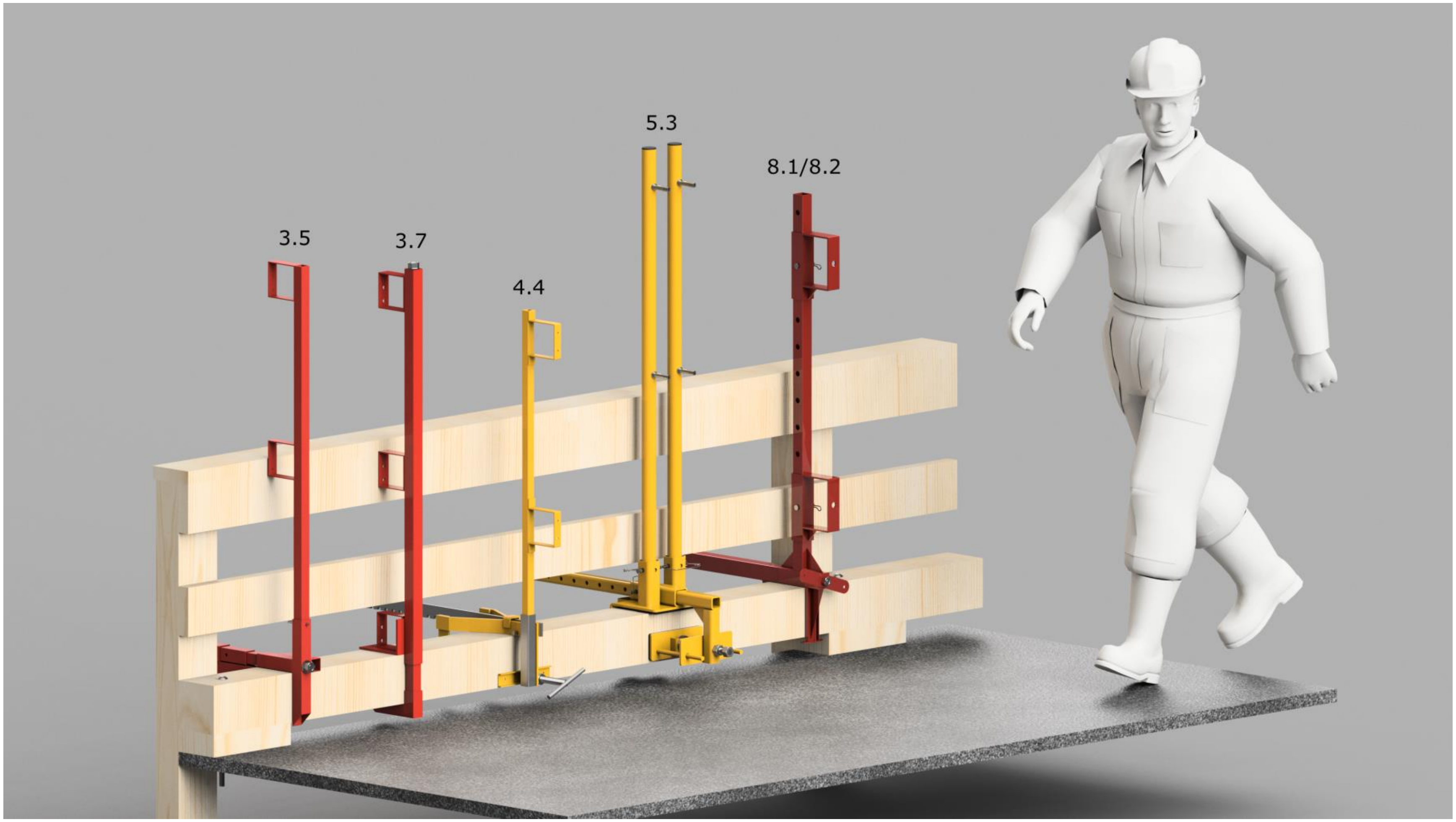


Figure 64 – Guardrail Type 22, wheel guard fit; view from the southeast

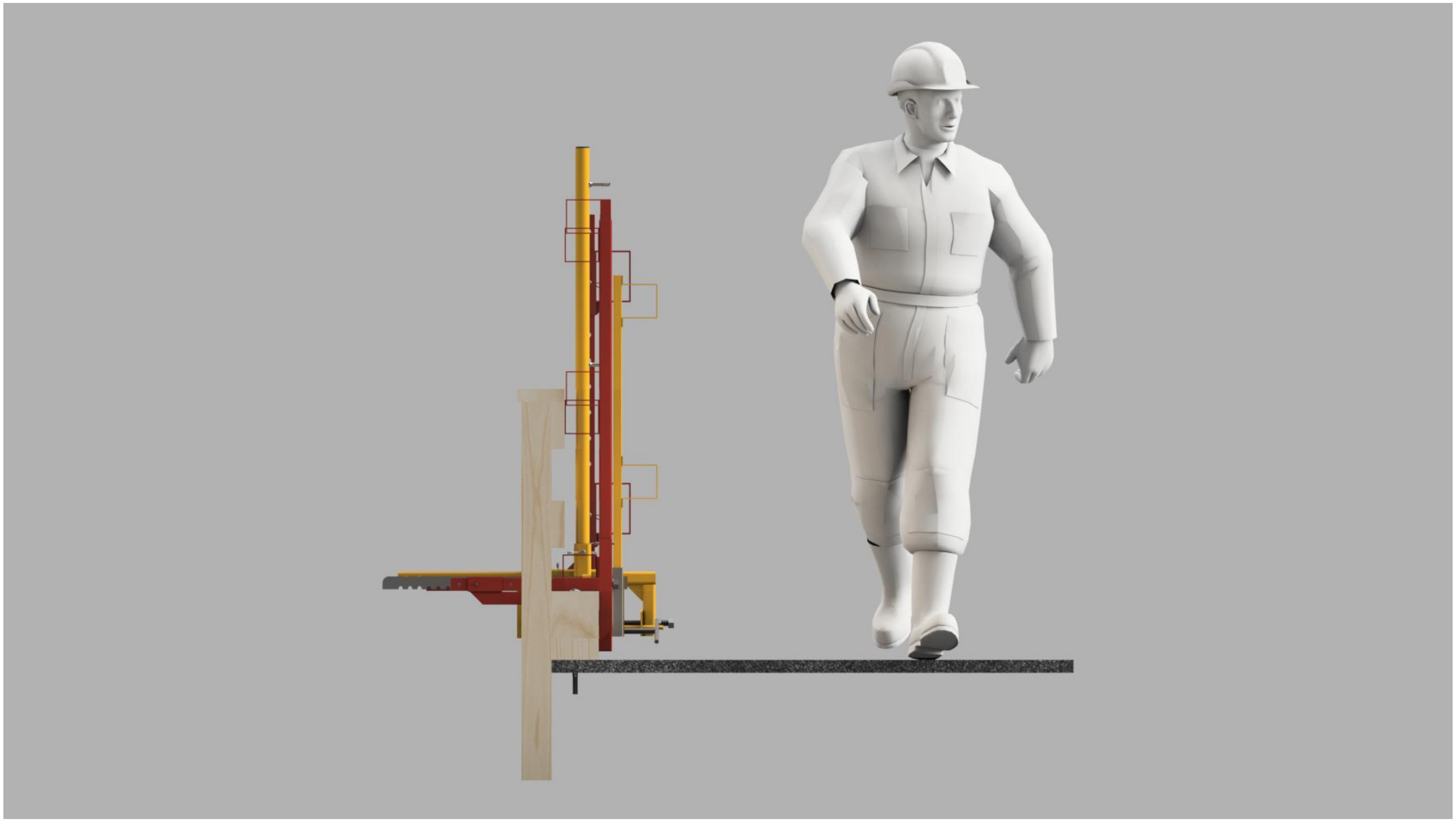


Figure 65 – Guardrail Type 22, wheel guard fit; view from the south

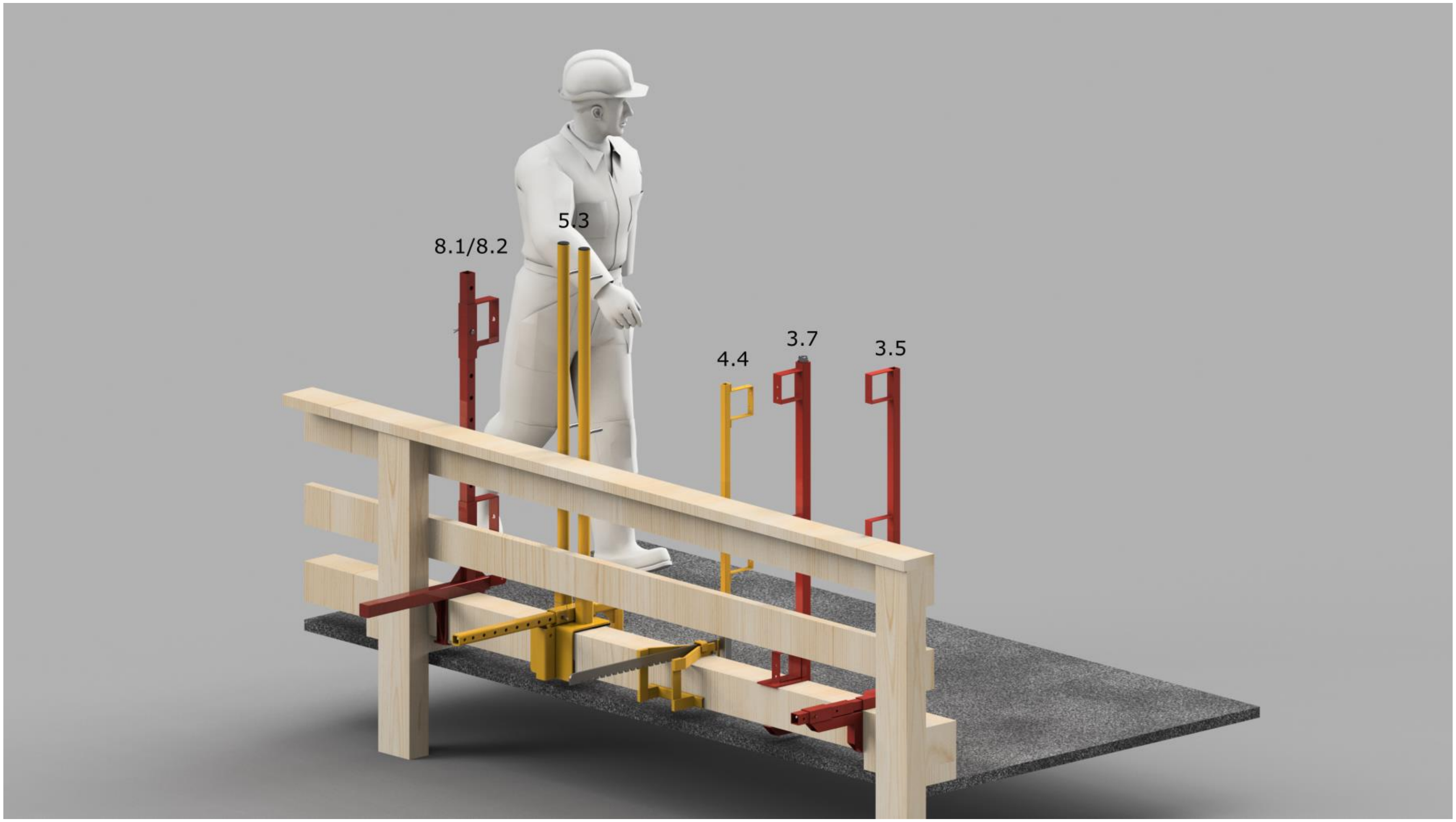


Figure 66 – Guardrail Type 22, wheel guard fit; view from the southwest

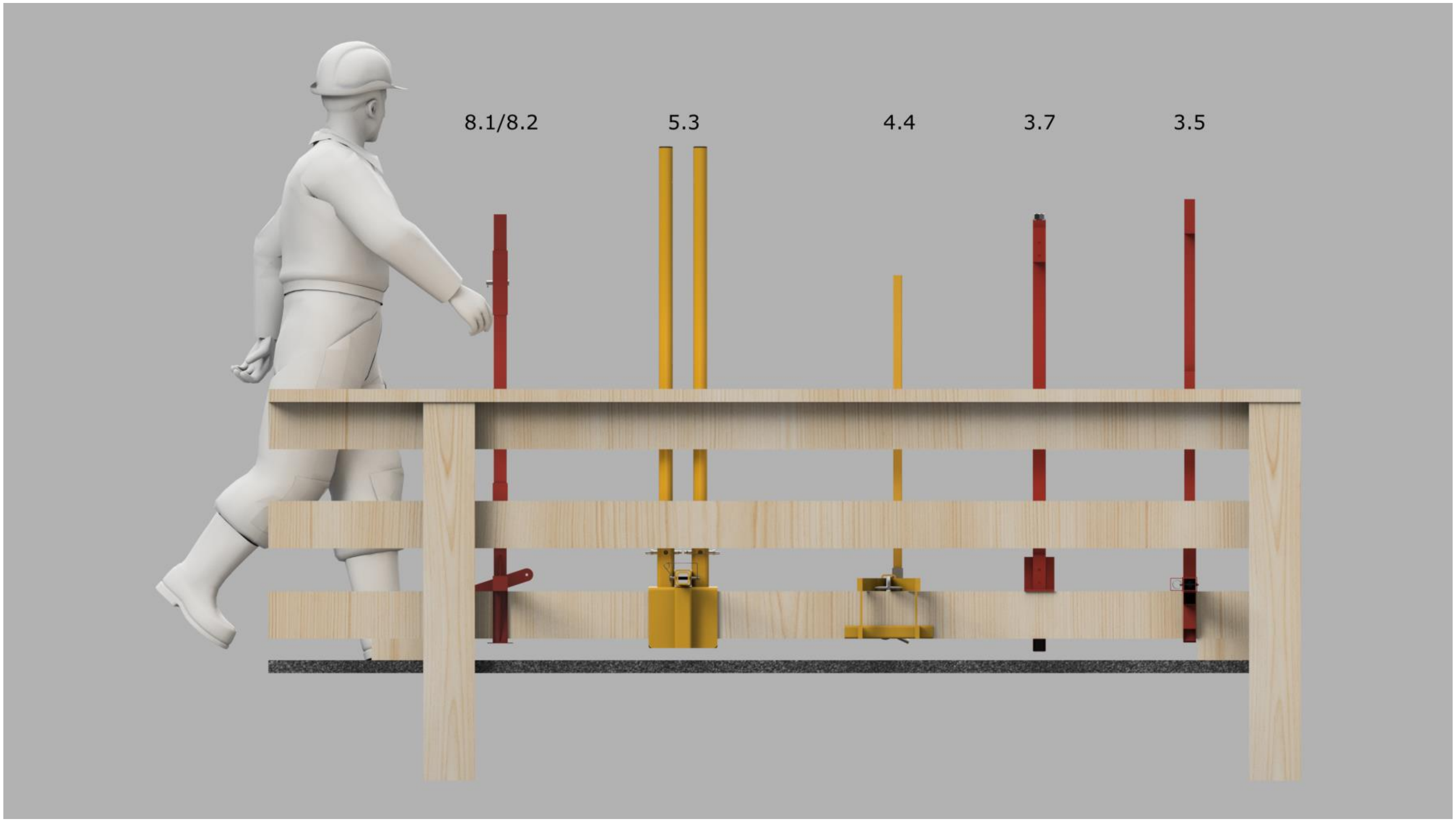


Figure 67 – Guardrail Type 22, wheel guard fit; view from the west

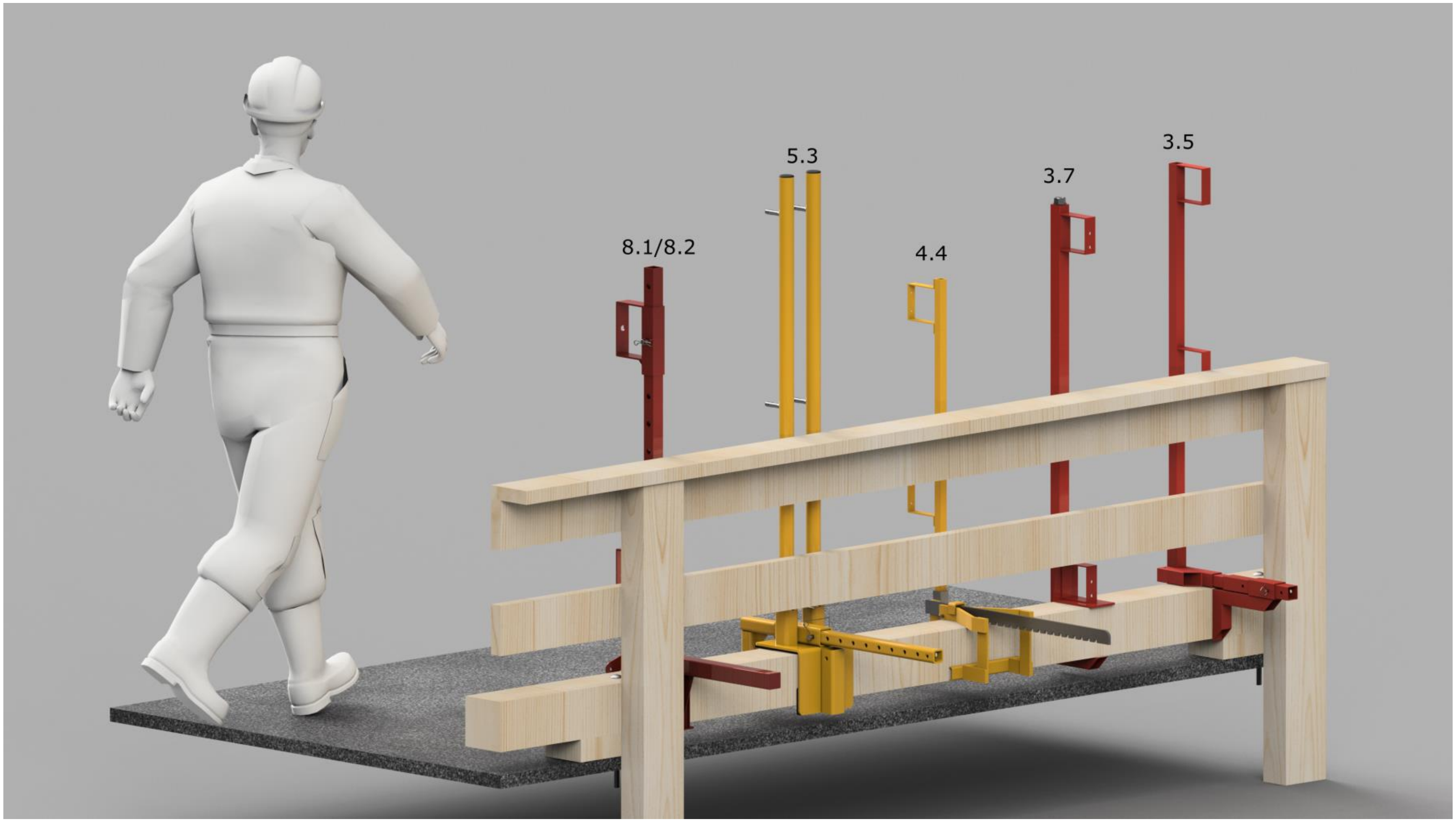


Figure 68 – Guardrail Type 22, wheel guard fit; view from the northwest

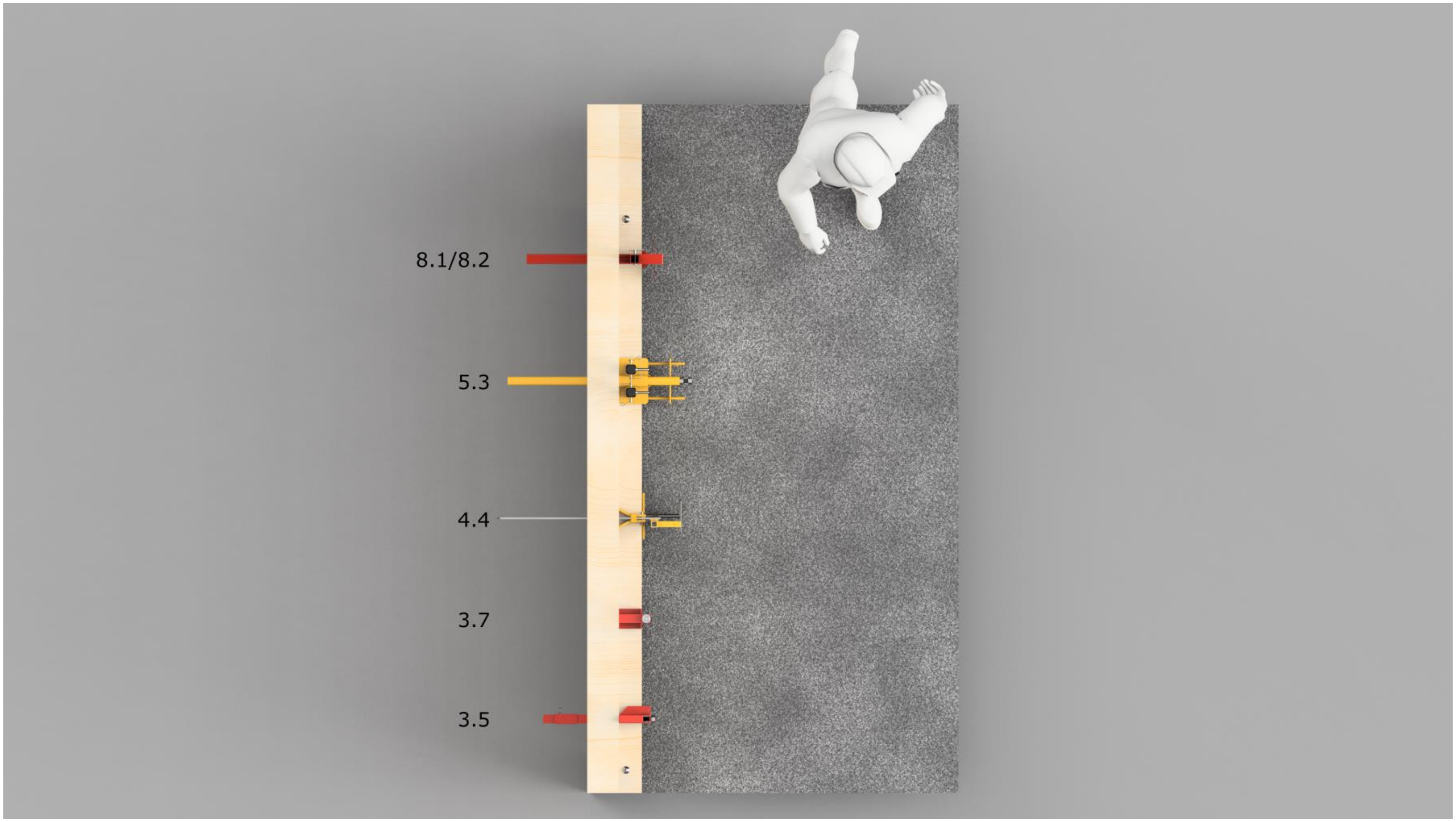


Figure 69 – Guardrail Type 22, wheel guard fit; view from the top

10. GUARDRAIL TYPE 23 – W-beam

10.1 Description

Commonly referred to as "W-beam" bridge rail, the guardrail is comprised of a W-shape steel section bolted to structural steel grade posts. This guardrail shape is also used in longitudinal barriers along highways and transitions from longitudinal barriers to bridge guardrails. After reviewing routine inspection reports and performing a site visit in Wake County, we found two varying field conditions. First, the wheel guard can vary between an L-angle and a small concrete curb. Second, guardrail post can vary between a W-section shape and an L-section. See details on Figure 71 and Figure 72. Because we did not find drawings for this type guardrail with a concrete curb and an L-section post, all compatibility testing was performed with the L-angle wheel guard. In addition, fitment of the FPSD over the W6 post was not evaluated.

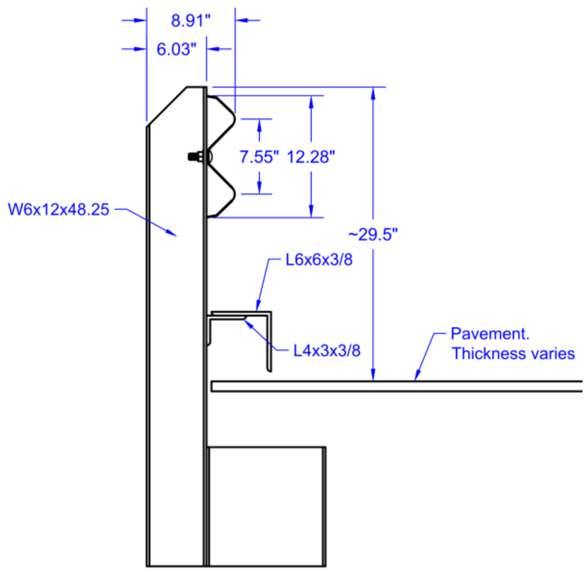


Figure 70 - Guardrail Type 23 section

Figure 71 - Guardrail Type 23 with concrete curb wheel guard and L-section post.

Figure 72 - guardrail Type 23 with L-angle wheel guard and W-section post.

10.2 Compatibility Chart

Table 9 - Compatibility chart for Guardrail Type 23

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	**Guardrail:** This device fits over the guardrail. A 4”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 23.5”. **Wheel Guard:** This device fits over the wheel guard. Intrusion into the work area is approximately 24”.
3.1	C-Clamp - CC120	**Guardrail:** This device fits over the guardrail. A 6”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 4.25”. **Wheel Guard:** This device fits over the wheel guard. A 2”W x 6”L (maximum length) lumber piece is required in front of the L-angle. Intrusion into the work area is approximately 3.75”.
3.3	Master C-Clamp - MCC130	**Guardrail:** This device fits over the guardrail. A 6”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 4.25”. **Wheel Guard:** This device fits over the wheel guard. A 4”W x 6”L (maximum length) lumber piece is needed in front of the L-angle. Intrusion into the work area is approximately 5.75”.
4.3	Alligator Parapet Guardrail system - 15167	**Guardrail:** The device fits over the guardrail. 2”W x 8”L lumber pieces are needed; one in front of the guardrail and one in the back of the guardrail. Intrusion into the work area is approximately 5.25”. **Wheel Guard:** This device **does not fit** over the wheel guard. There is interference between the device’s post and the W-shape guardrail.
4.4	Parapet Clamp Guardrail System - 15170	**Guardrail:** The device fits over the guardrail. 2”W x 8”L lumber pieces are needed; one in front of the guardrail and one in the back of the guardrail. Intrusion into the work area is approximately 4.25”. **Wheel Guard:** This device fits over the guardrail. Intrusion into the work area is approximately 9”
4.5	Parapet Anchor - 15171	**Guardrail:** The device fits over the guardrail. A 2”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 14.5”. **Wheel Guard:** This device **does not fit** over the wheel guard. There is interference between the device’s post and the W-shape guardrail.
5.1	RaptorRail	**Guardrail:** The device fits over the guardrail. A 2”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 6.5”. **Wheel Guard:** This device **does not fit** over the wheel guard. There is interference between the device’s post and the W-shape guardrail.
5.2	All-In-One	**Guardrail:** The device fits over the guardrail. Intrusion into the work area is approximately 5”. **Wheel Guard:** This device **does not fit** over the wheel guard. There is interference between the device’s post and the W-shape guardrail.
5.3	Universal Guardrail Parapet Clamp	**Guardrail:** The device fits over the guardrail. A 4”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 8.75”. **Wheel Guard:** This device fits over the wheel guard. Intrusion into the work area is approximately 8-¾”
8.1	Parapet Guardrails GRS-P12	**Guardrail:** This device fits over the guardrail. A 2”W x 8”L lumber piece is needed in front of the guardrail. The tightening handle faces the inside of the bridge. Intrusion into the work area is approximately 1.5”. **Wheel Guard:** The device fits over the wheel guard. Intrusion into the work area is approximately 3.75”.

ID	PRODUCT NAME	COMPATIBILITY NOTES
8.2	Parapet Guardrails GRS-P24	**Guardrail:** This device fits over the guardrail. A 2”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 1.5”. **Wheel Guard:** The device fits over the wheel guard. Intrusion into the work area is approximately 3.75”.
8.3	QuickRail Parapet Guardrail QR-P12	**Guardrail:** This device fits over the guardrail. A 2”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 0.5”. **Wheel Guard:** This device **does not fit** over the wheel guard. There is interference between the device’s wood post and the W-shape guardrail.
8.4	QuickRail Parapet Guardrail QR-P24	**Guardrail:** This device fits over the guardrail. A 2”W x 8”L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately ½”. **Wheel Guard:** This device **does not fit** over the wheel guard. There is interference between the device’s wood post and the W-shape guardrail.

10.3 Renderings

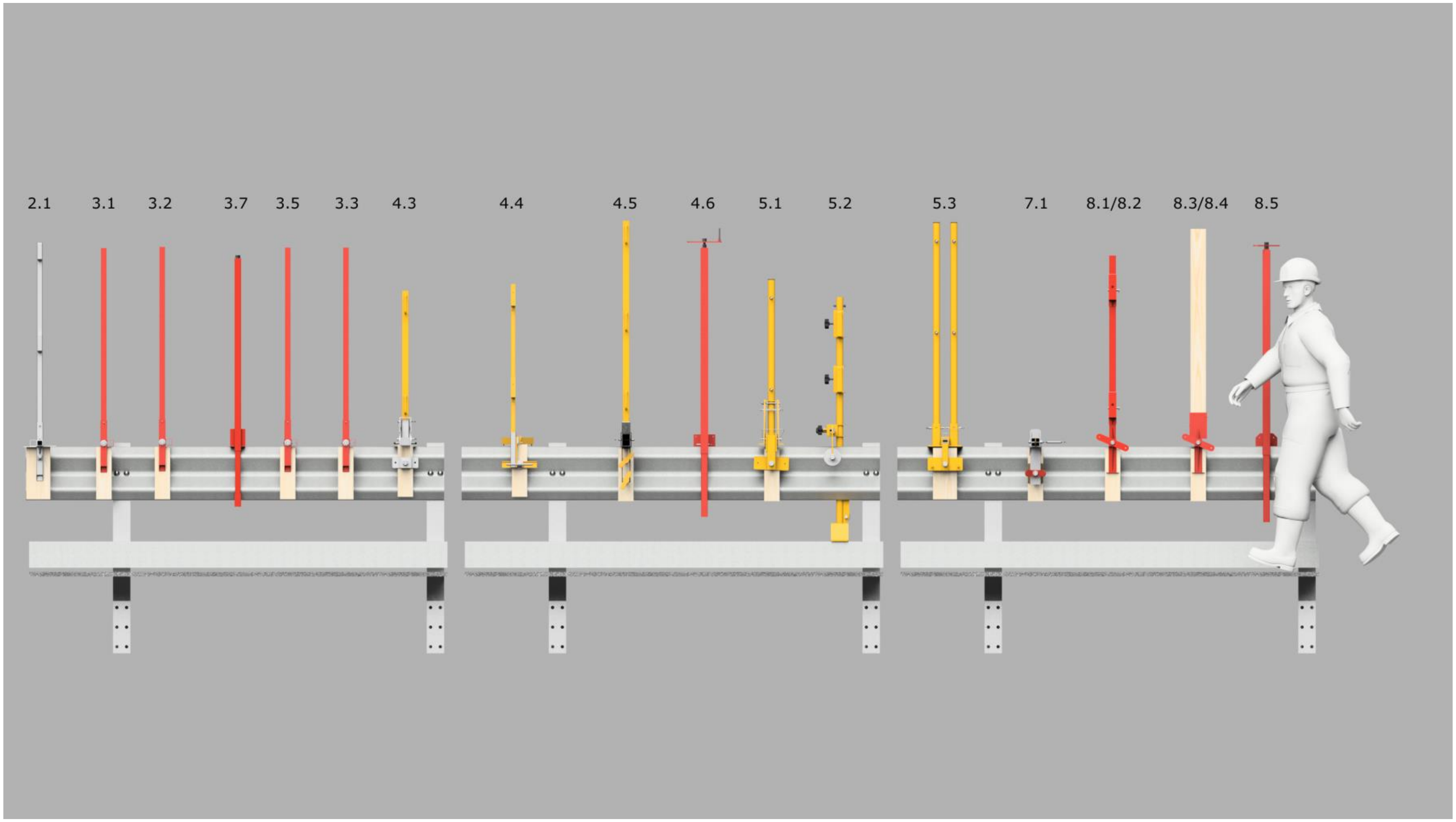


Figure 73 - Guardrail Type 23, guardrail fit; view from the east

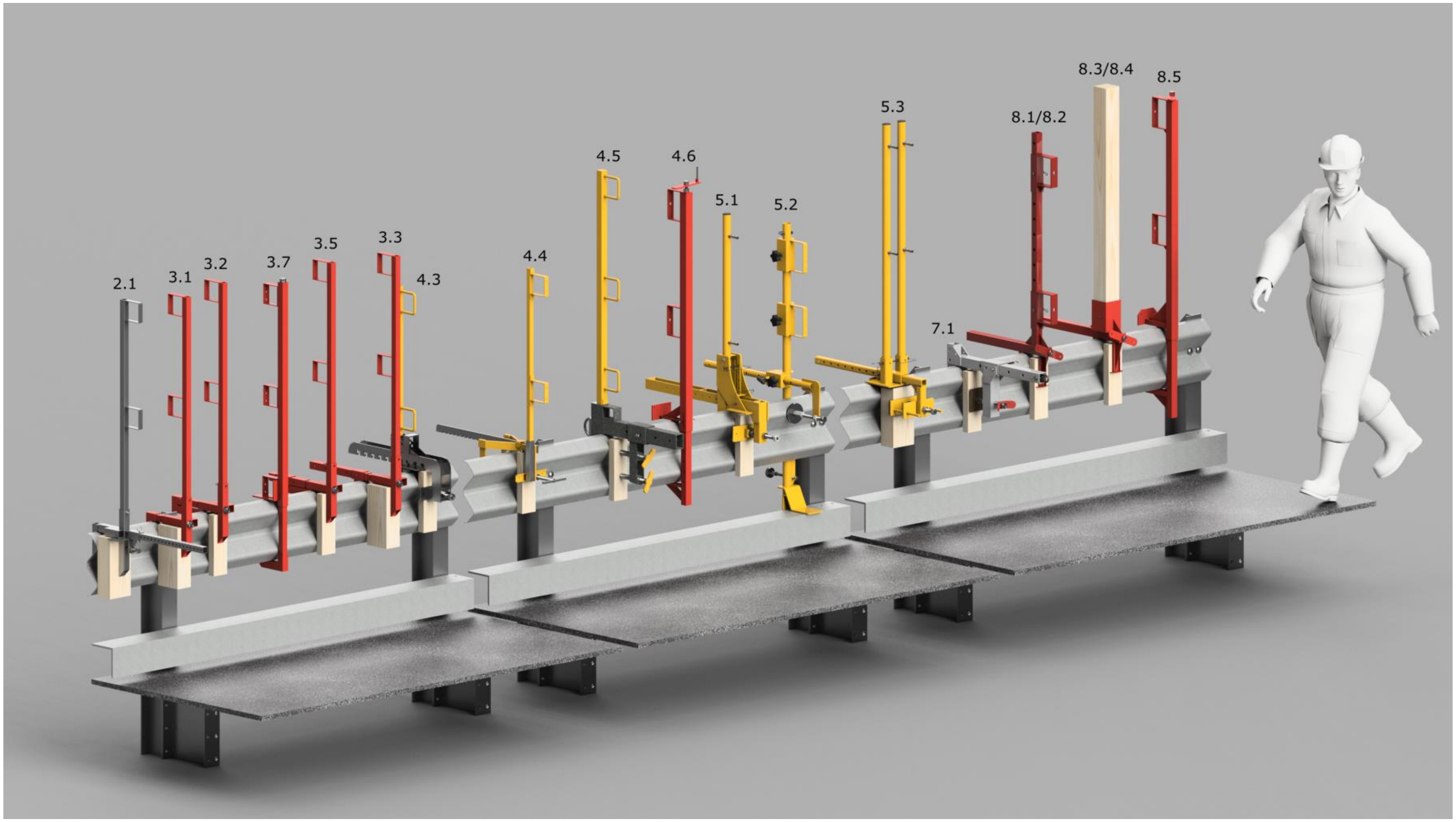


Figure 74 - Guardrail Type 23, guardrail fit; view from the southeast

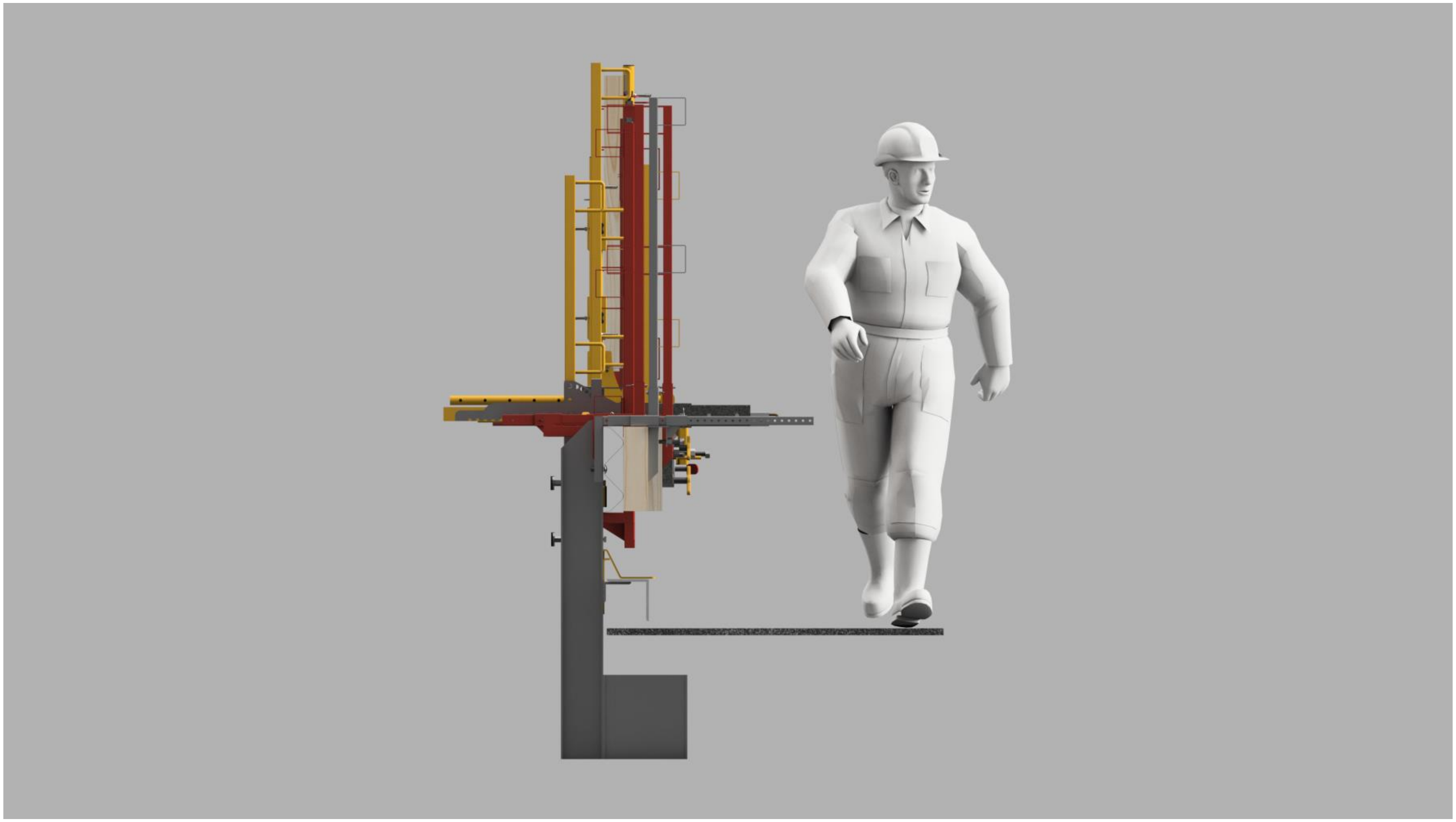


Figure 75 - Guardrail Type 23, guardrail fit; view from the south

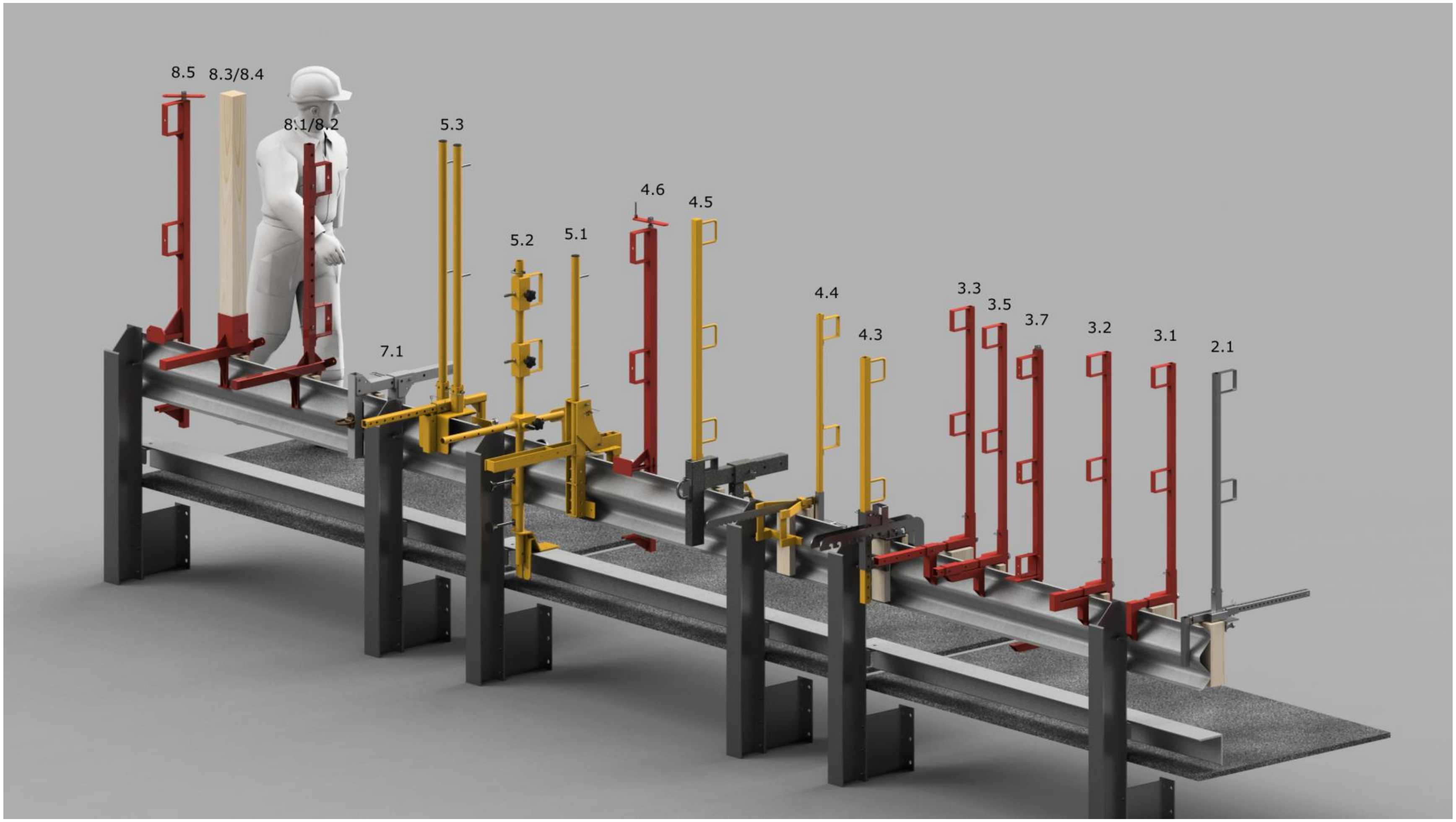


Figure 76 - Guardrail Type 23, guardrail fit; view from the southwest

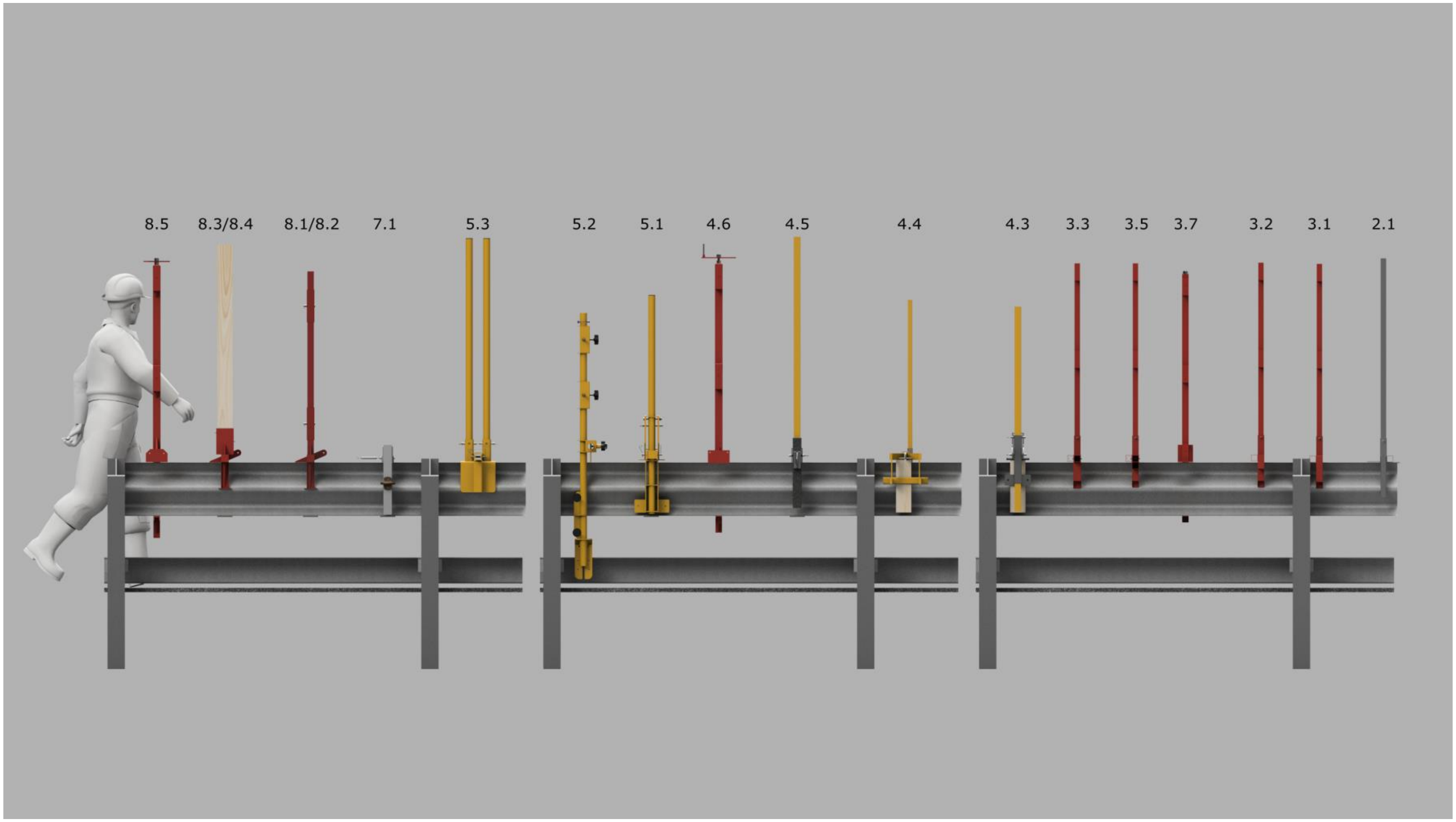


Figure 77 - Guardrail Type 23, guardrail fit; view from the west

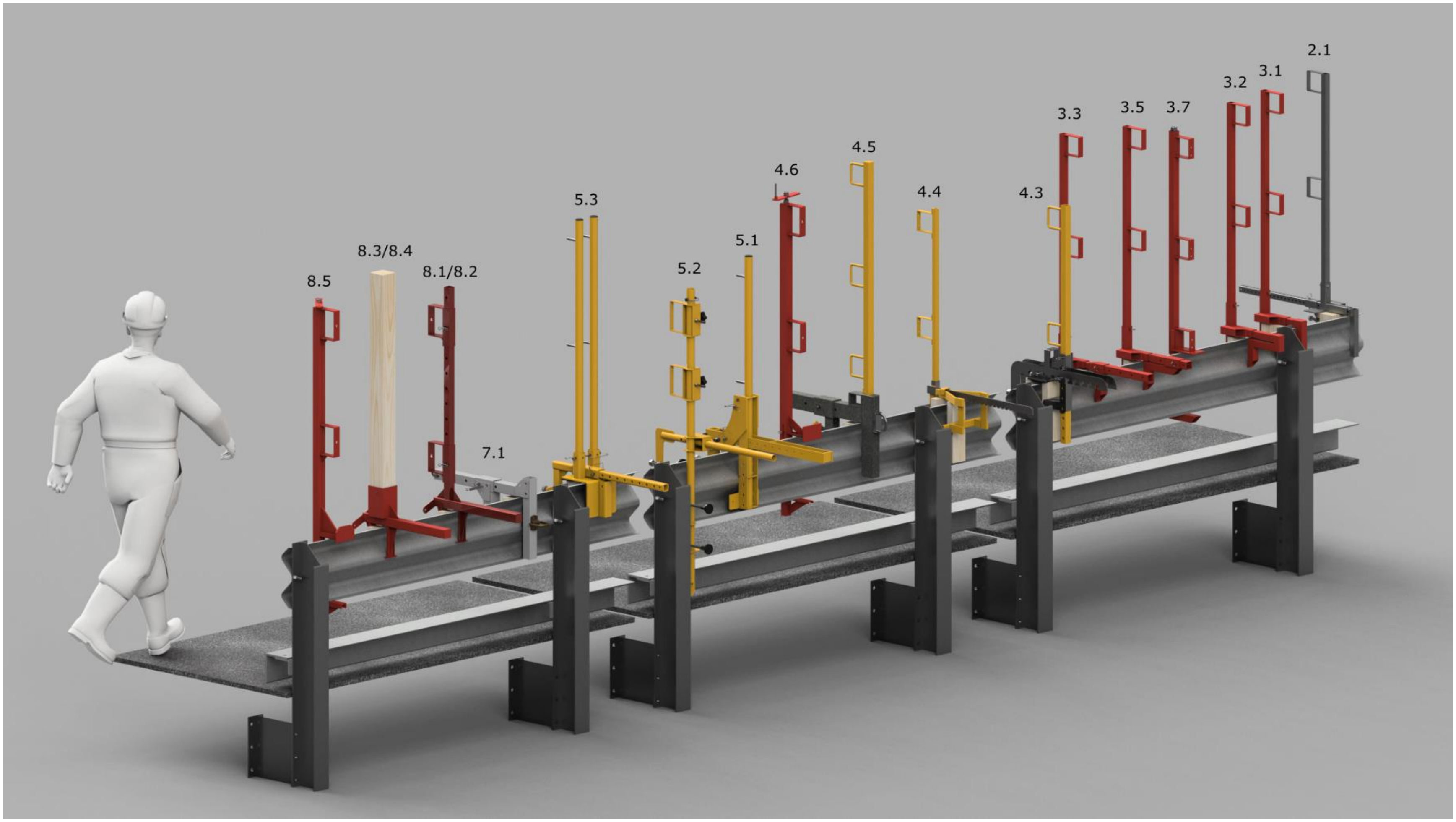


Figure 78 - Guardrail Type 23, guardrail fit; view from the northwest

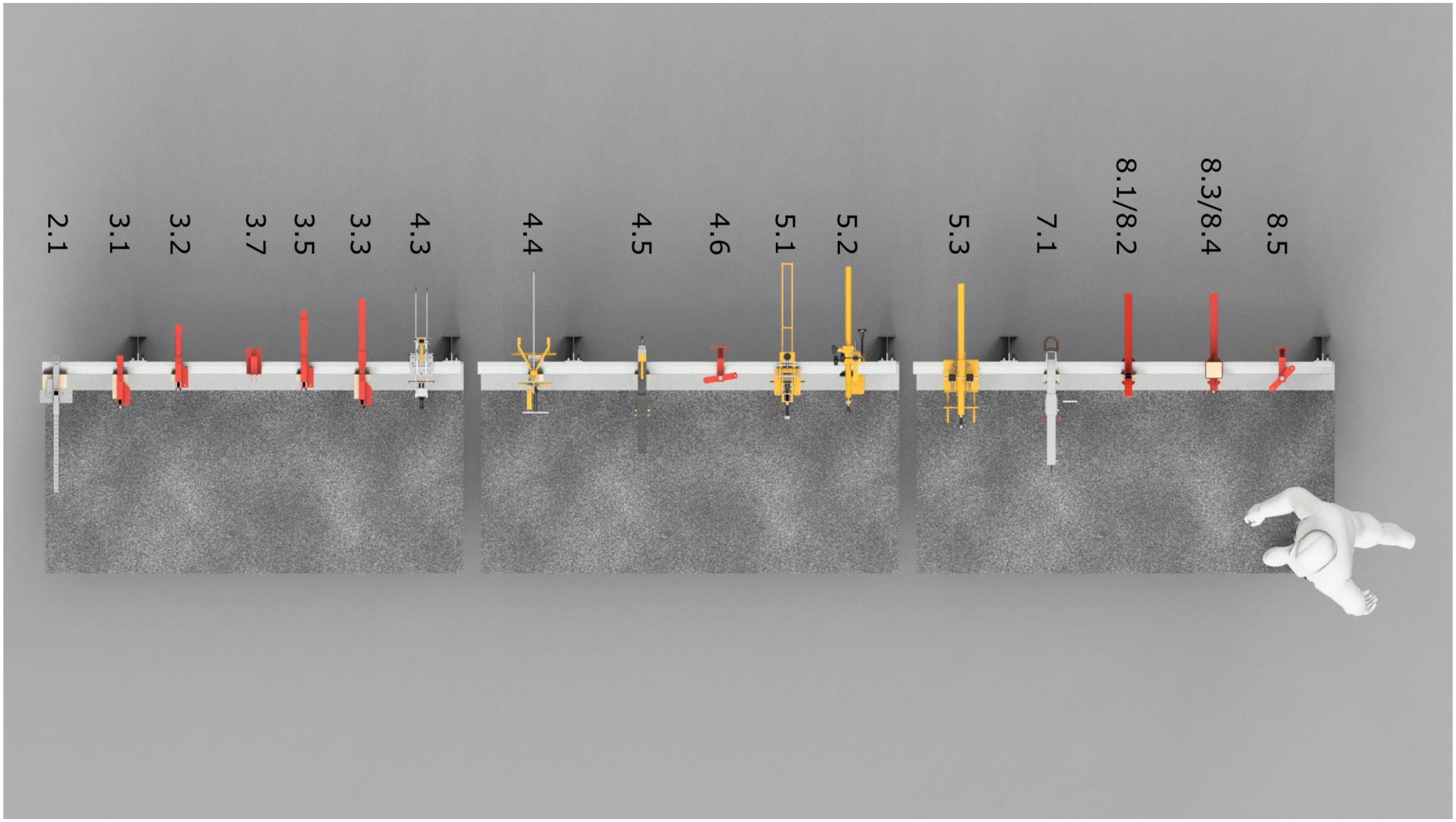


Figure 79 - Guardrail Type 23, guardrail fit; view from the top

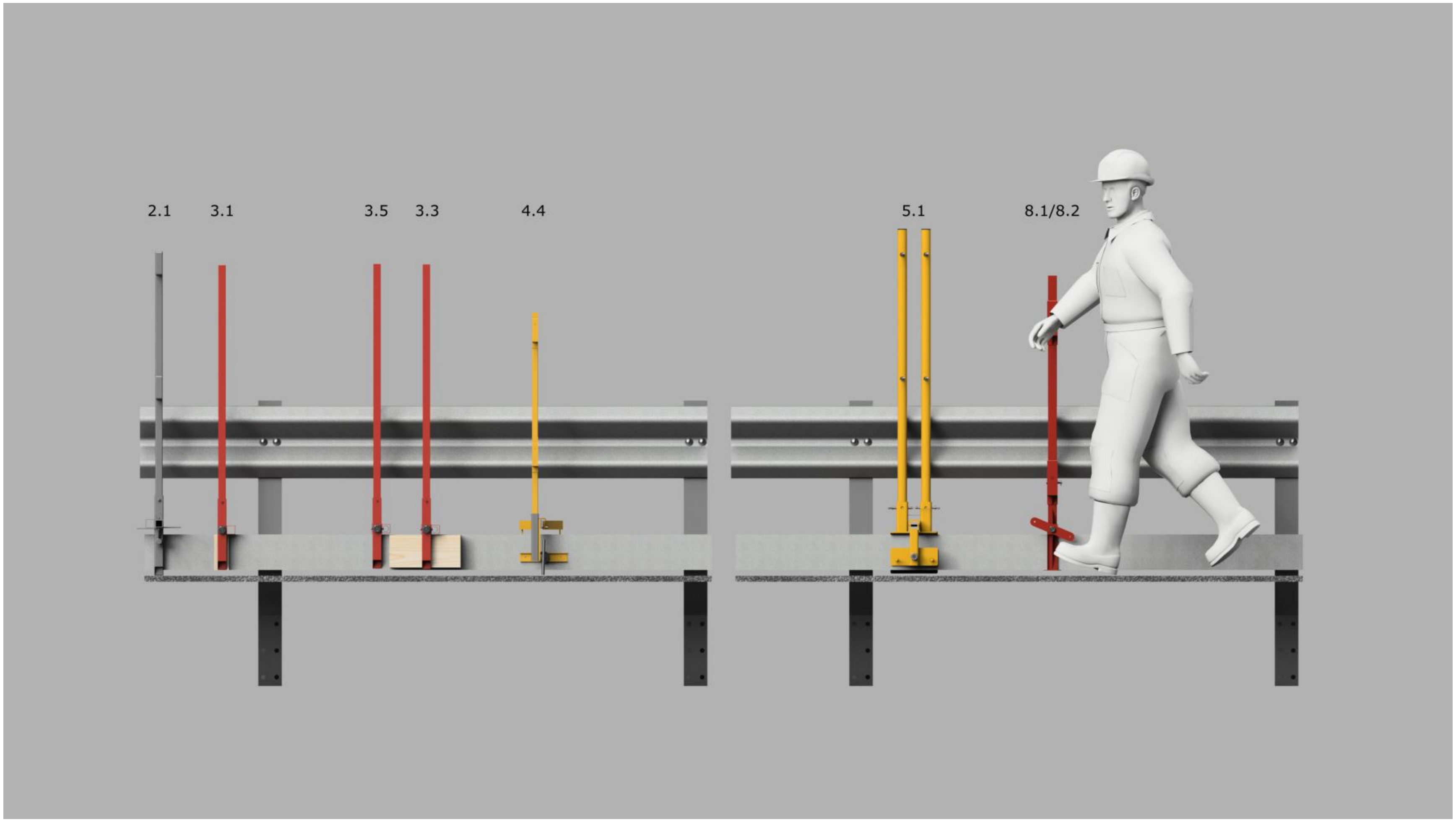


Figure 80 - Guardrail Type 23, wheel guard fit; view from the east

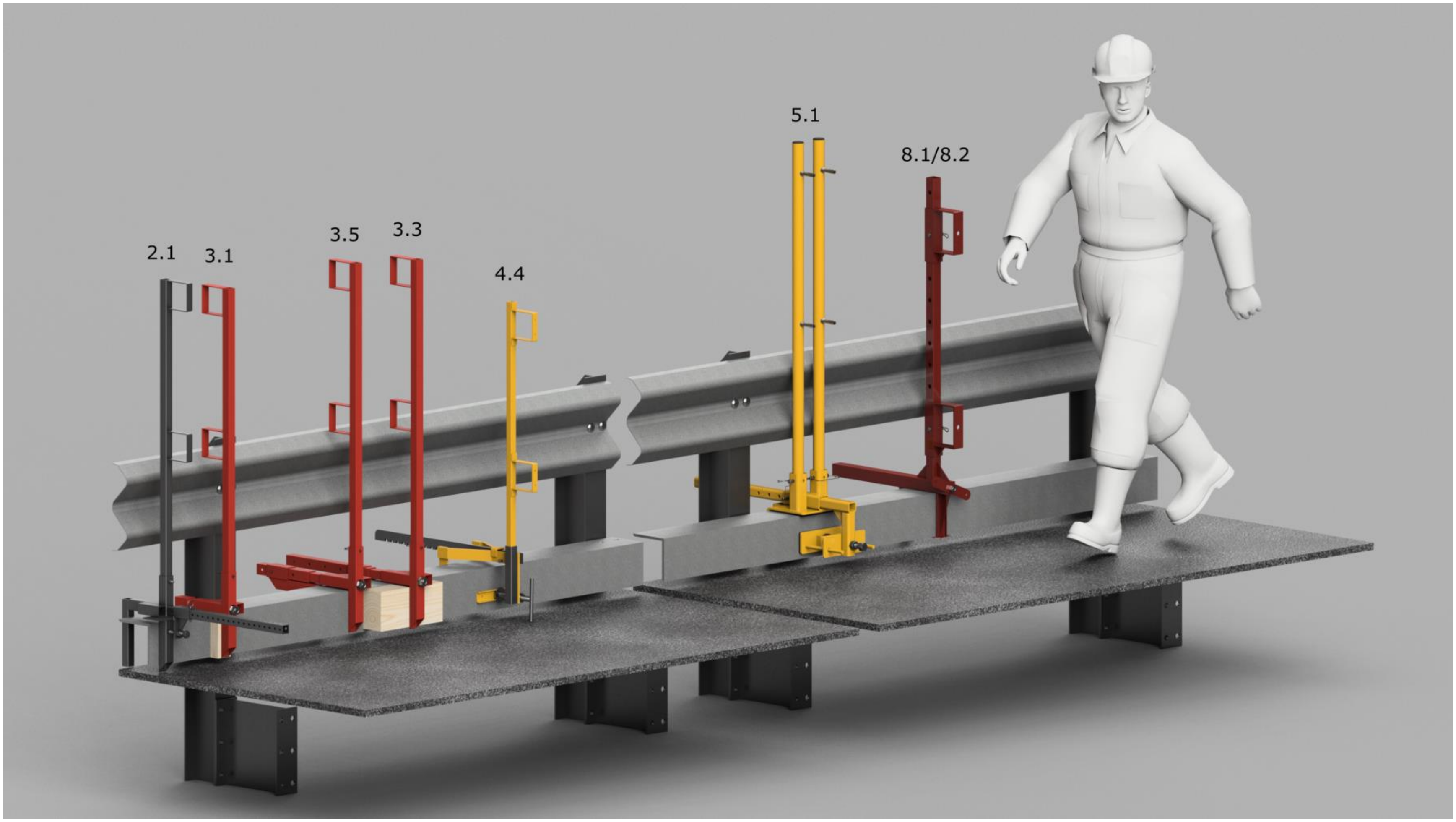


Figure 81 - Guardrail Type 23, wheel guard fit; view from the southeast

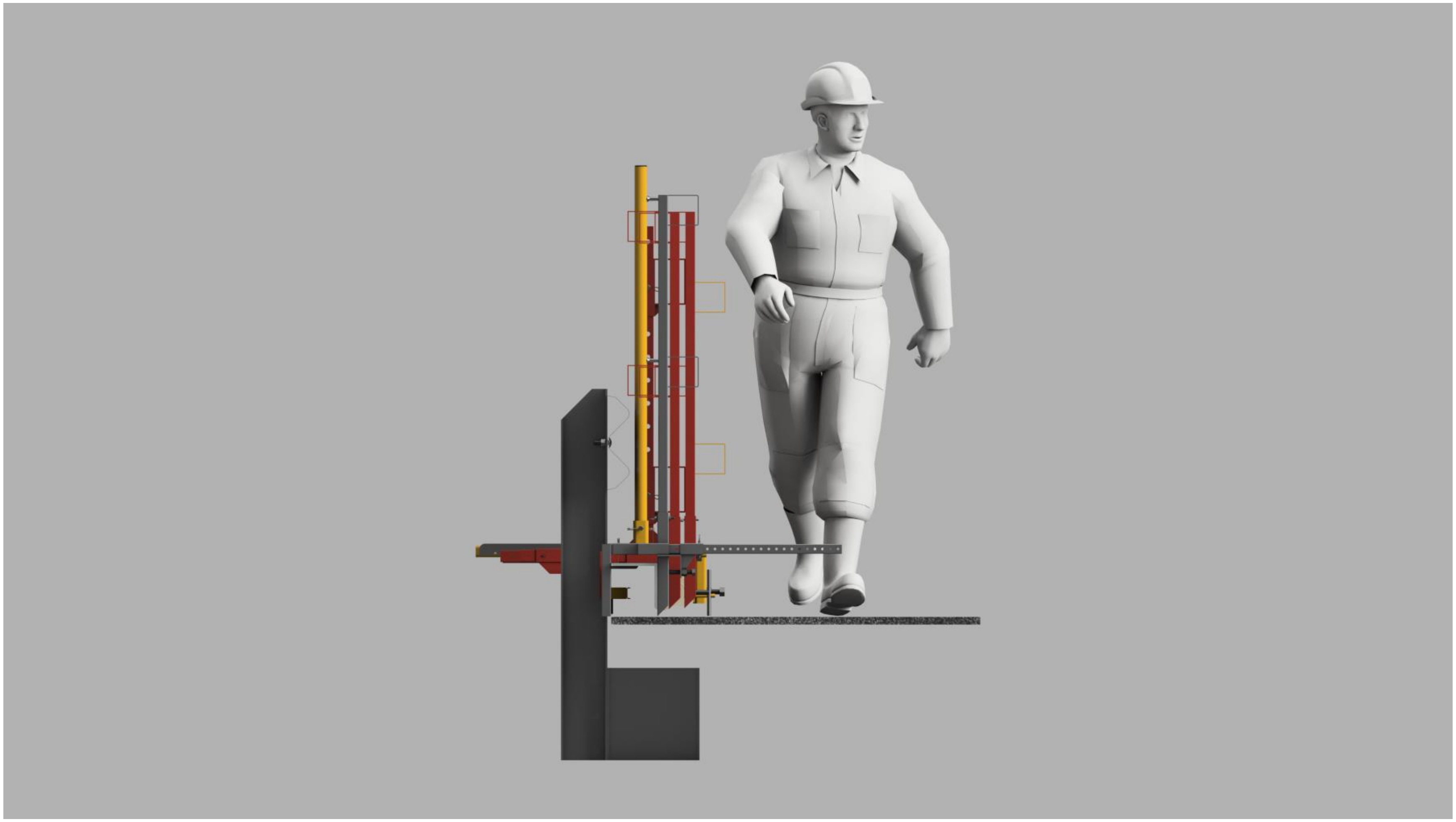


Figure 82 - Guardrail Type 23, wheel guard fit; view from the south

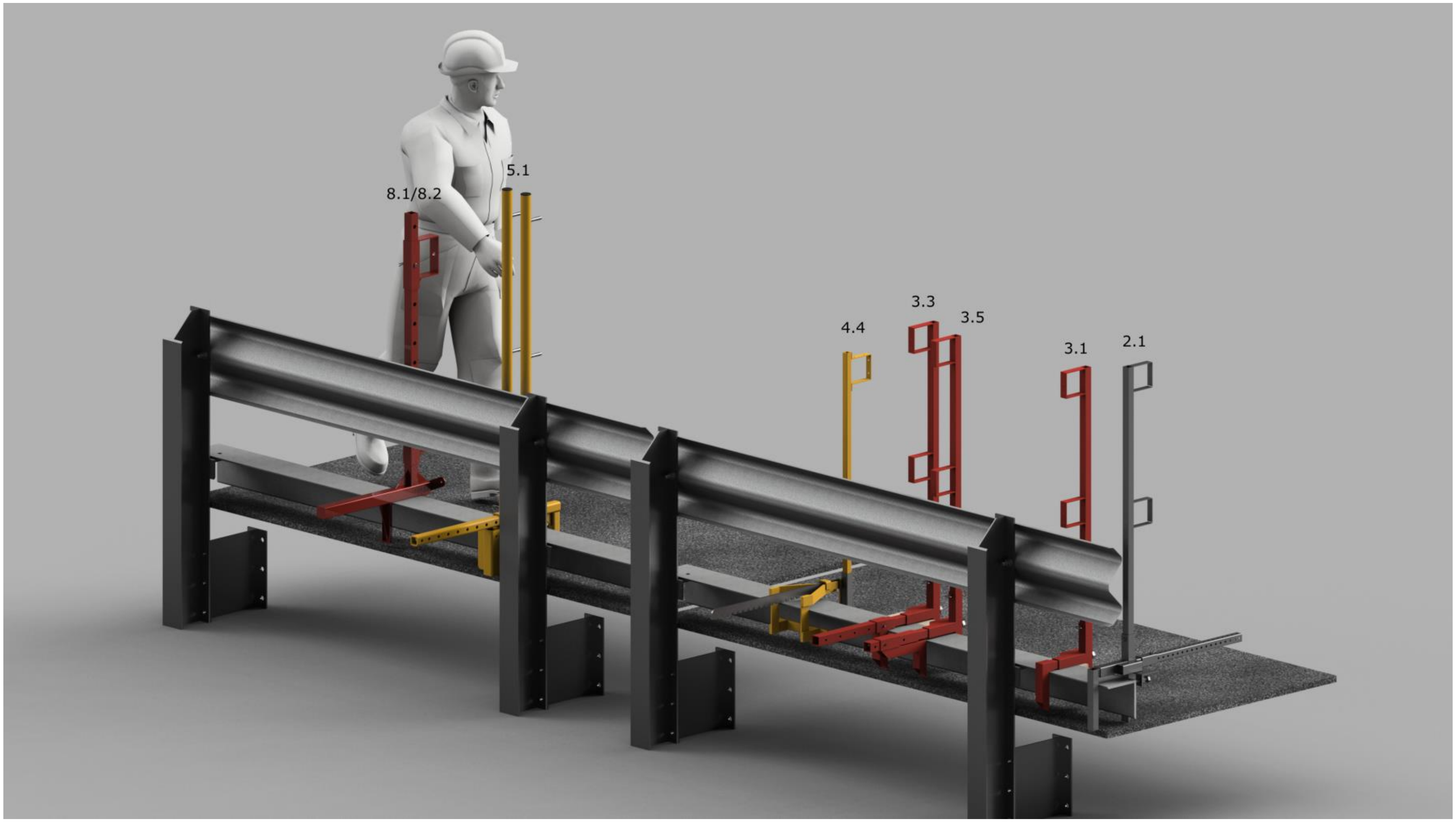


Figure 83 - Guardrail Type 23, wheel guard fit; view from the southwest

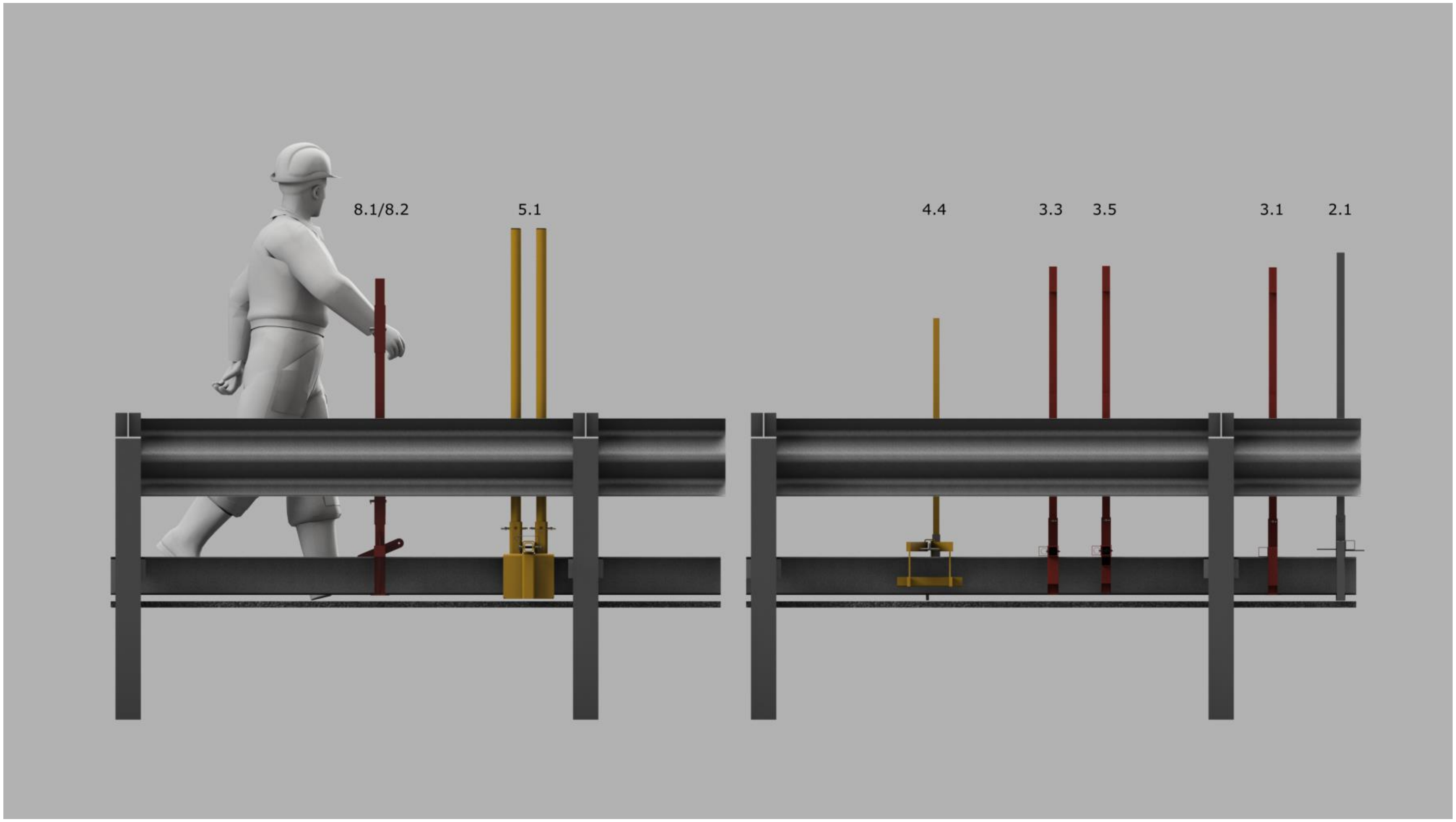


Figure 84 - Guardrail Type 23, wheel guard fit; view from the west

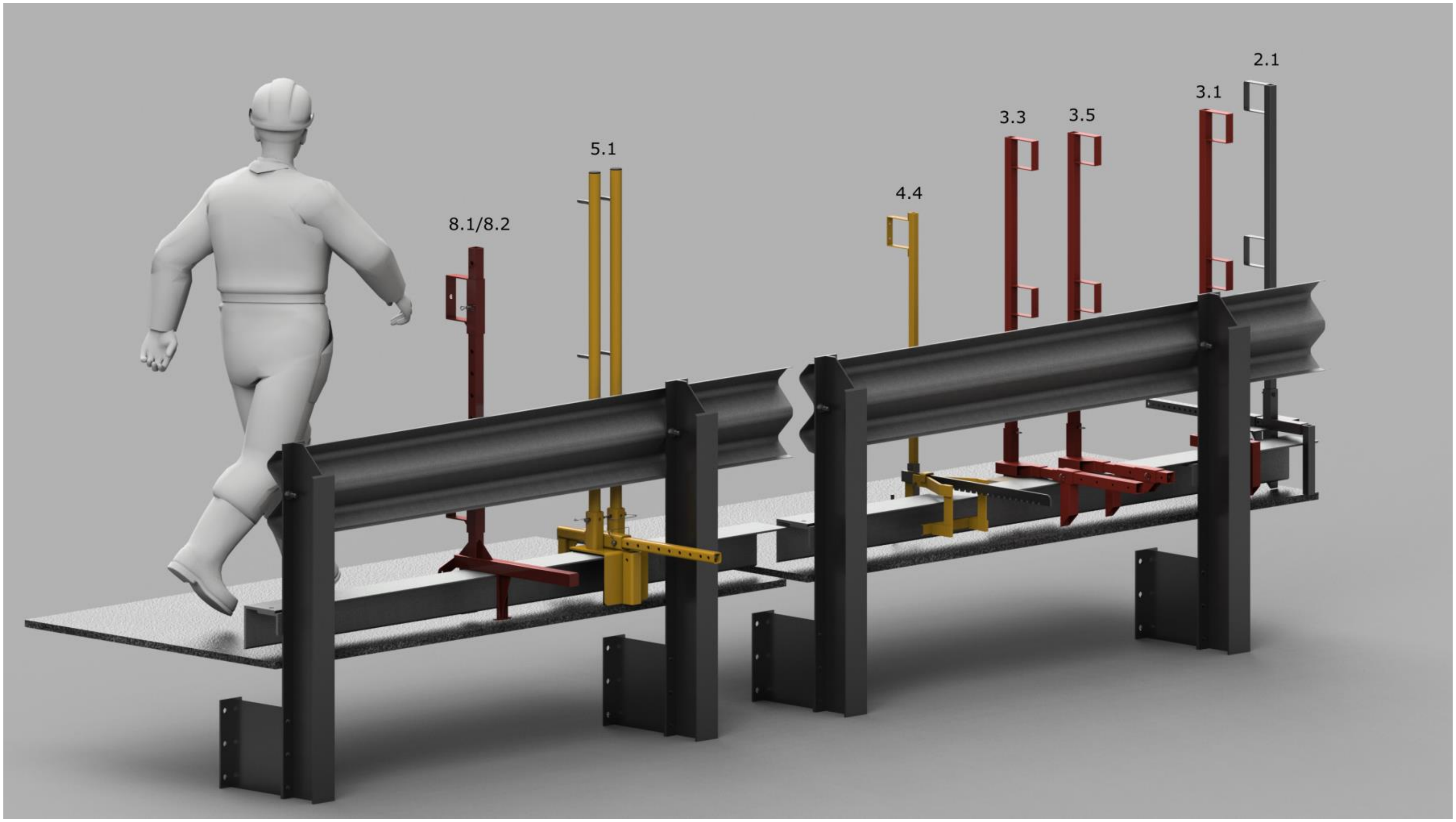


Figure 85 - Guardrail Type 23, wheel guard fit; view from the northwest

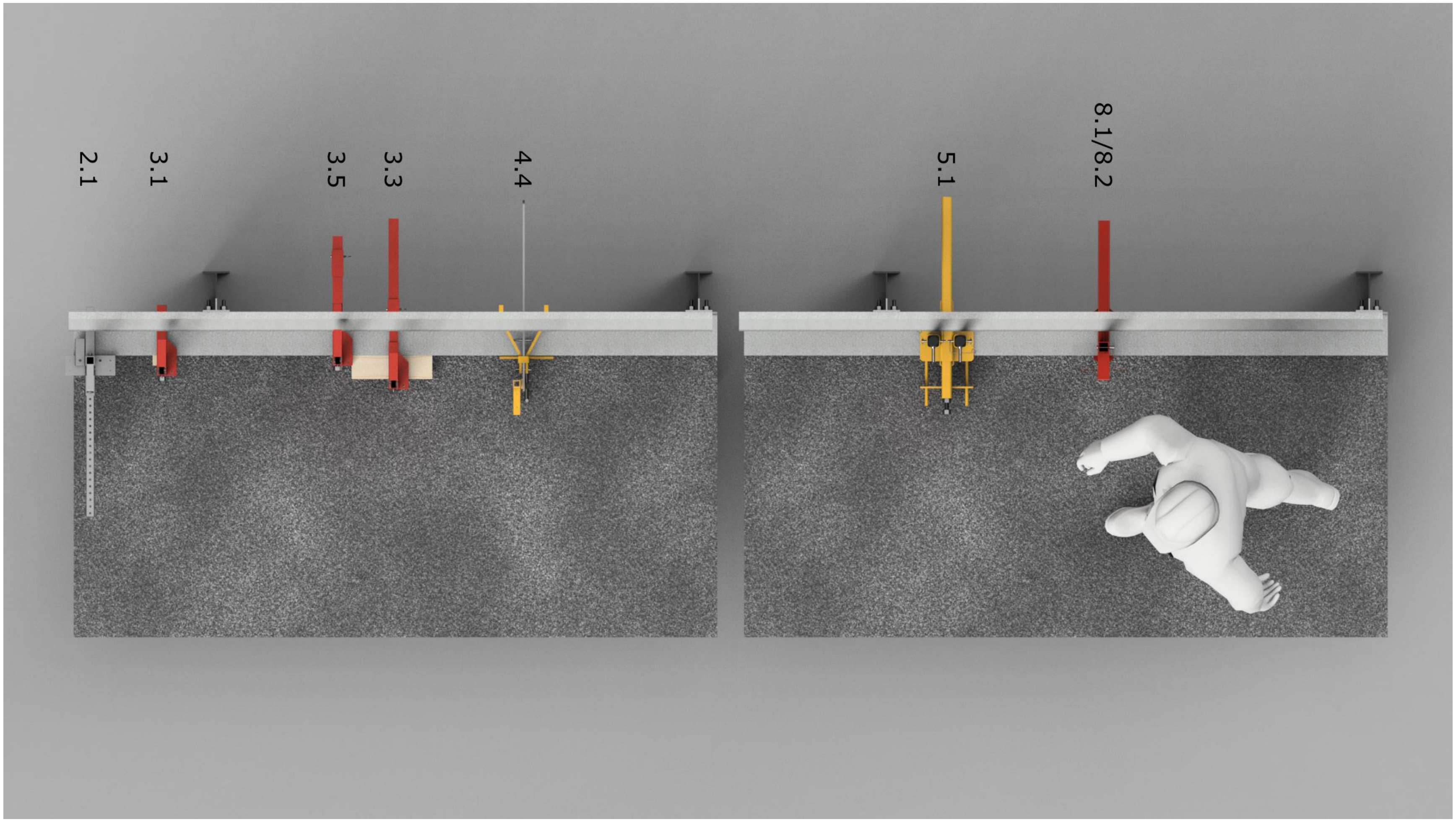


Figure 86 - Guardrail Type 23, wheel guard fit; view from the top

11. GUARDRAIL TYPE 24 – 1-Bar Concrete Rail (Middle)

11.1 Description

Concrete guardrail sections comprised of one reinforced concrete railing embedded at mid-height into two reinforced concrete supports, one at each end. After inspection of the Wiggins database, two variations of this guardrail designation were found as follows:

11.1.1 Guardrail Type 24, Variation 1

Variation 1 was found to be identical to Guardrail Type 14, variation 1. The latter was also found to have the same concrete post and bar rail characteristics as Guardrail Type 11. Therefore, refer to GUARDRAIL TYPE 11 – 1-Bar Concrete Rail (Middle) for compatibility testing results.

11.1.2 Guardrail Type 24, Variation 2

Variation 2 has the same concrete bar rail configuration as Variation 1. Although, the curb and post structure characteristics vary, the compatibility results are the same as Guardrail Type 11. Therefore, refer to GUARDRAIL TYPE 11 – 1-Bar Concrete Rail (Middle) for compatibility testing results.

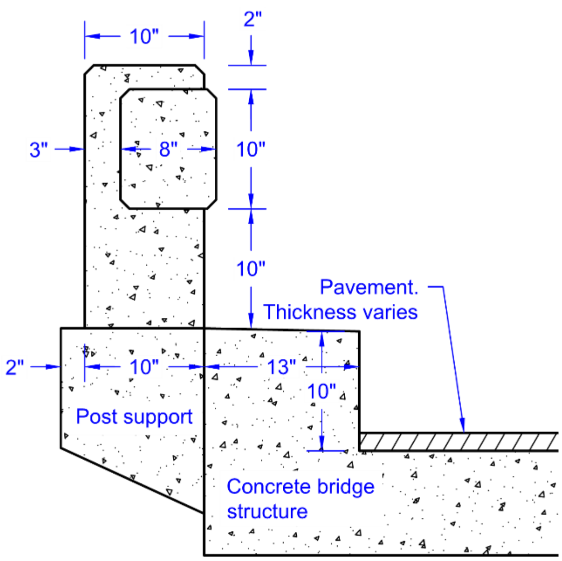


Figure 87 – Guardrail Type 24, variation 1 section

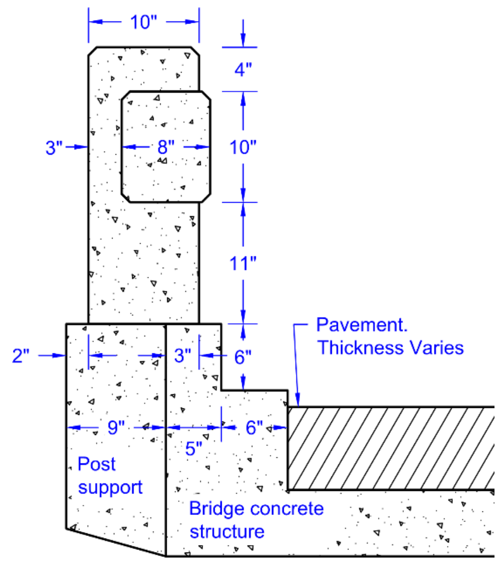


Figure 88 – Guardrail Type 24, variation 2 section

11.2 Renderings

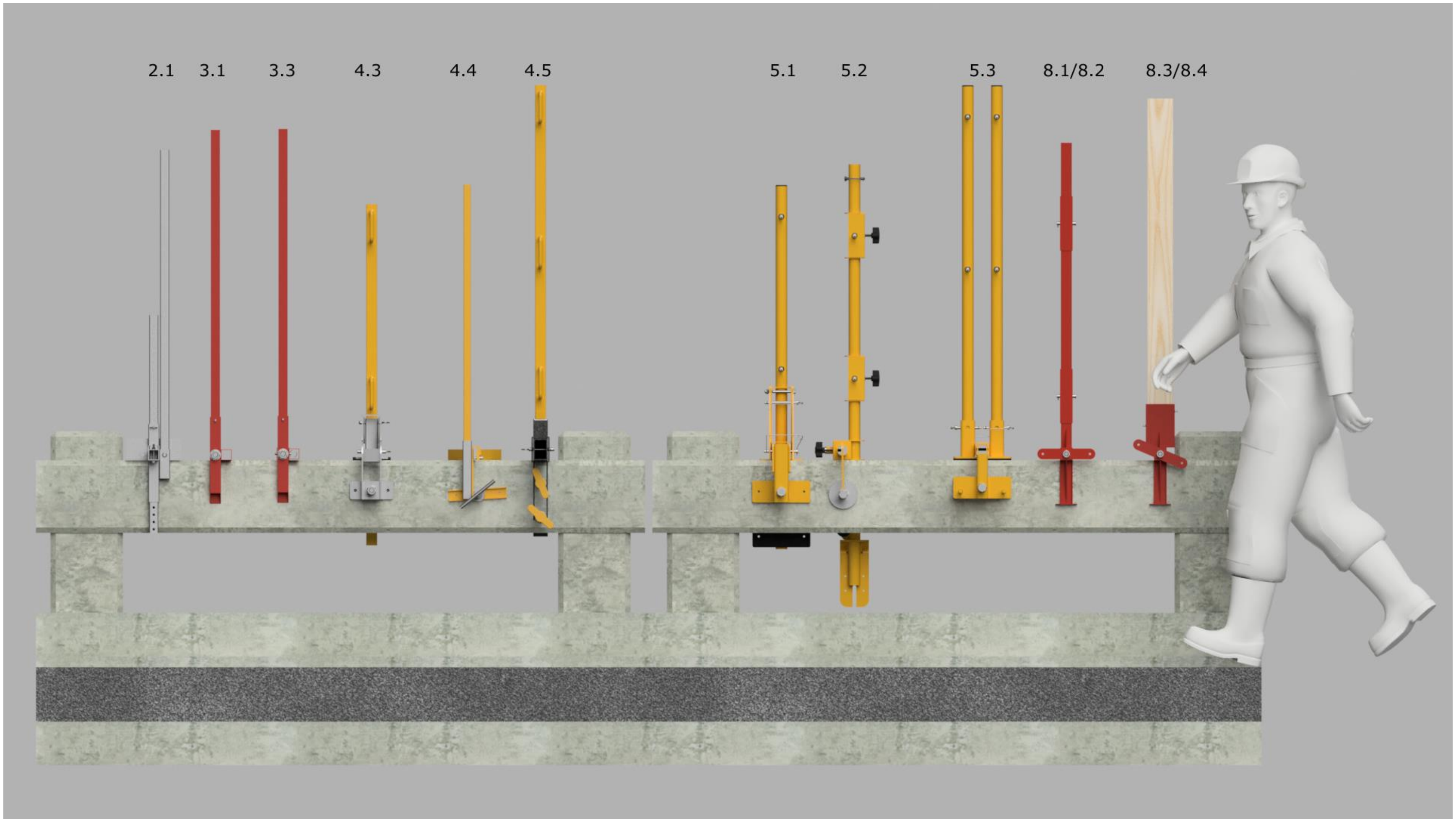


Figure 89 – Guardrail Type 24, variation 2; view from the east

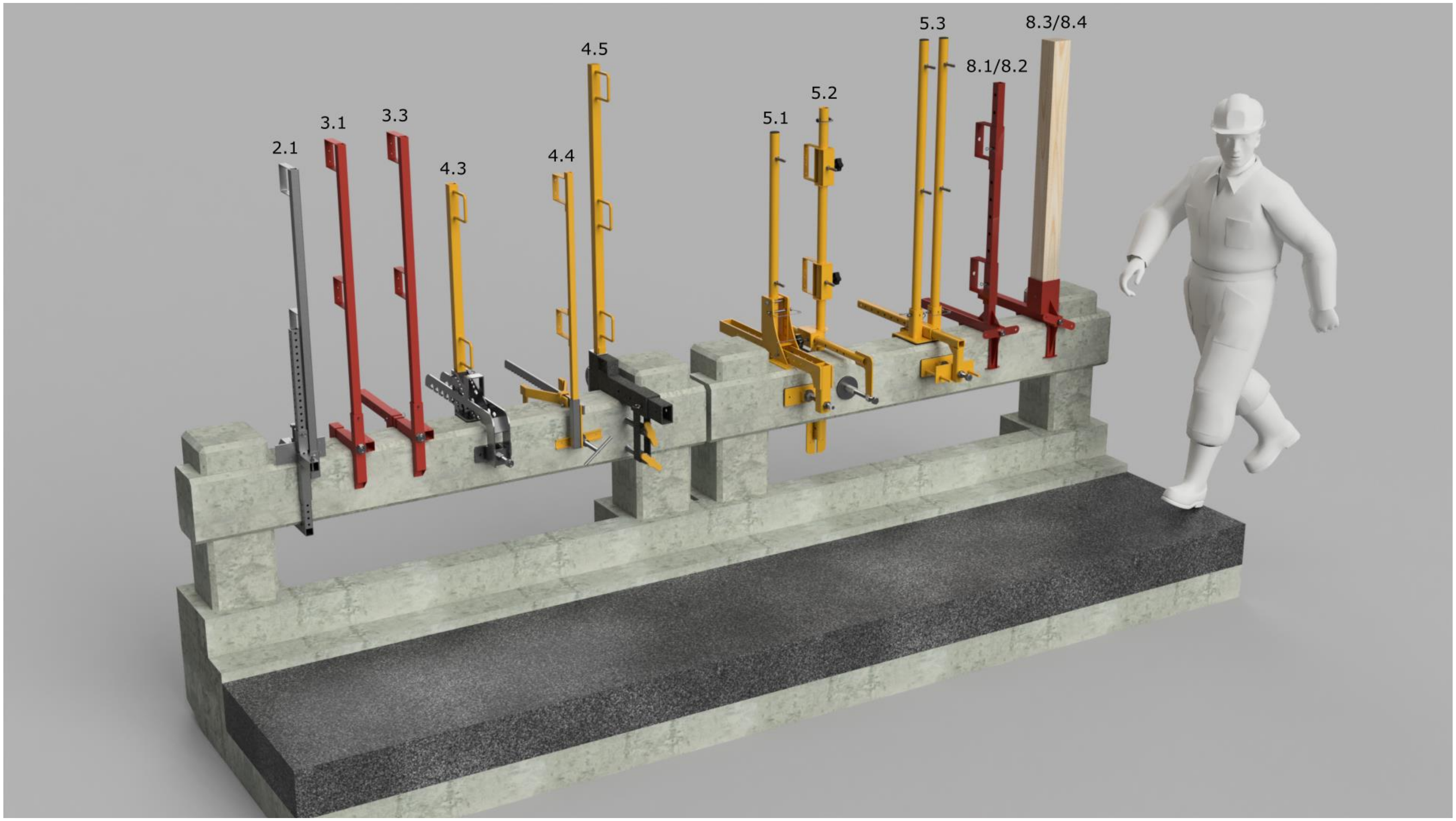


Figure 90 – Guardrail Type 24, variation 2; view from the southeast

Figure 91 – Guardrail Type 24, variation 2; view from the south

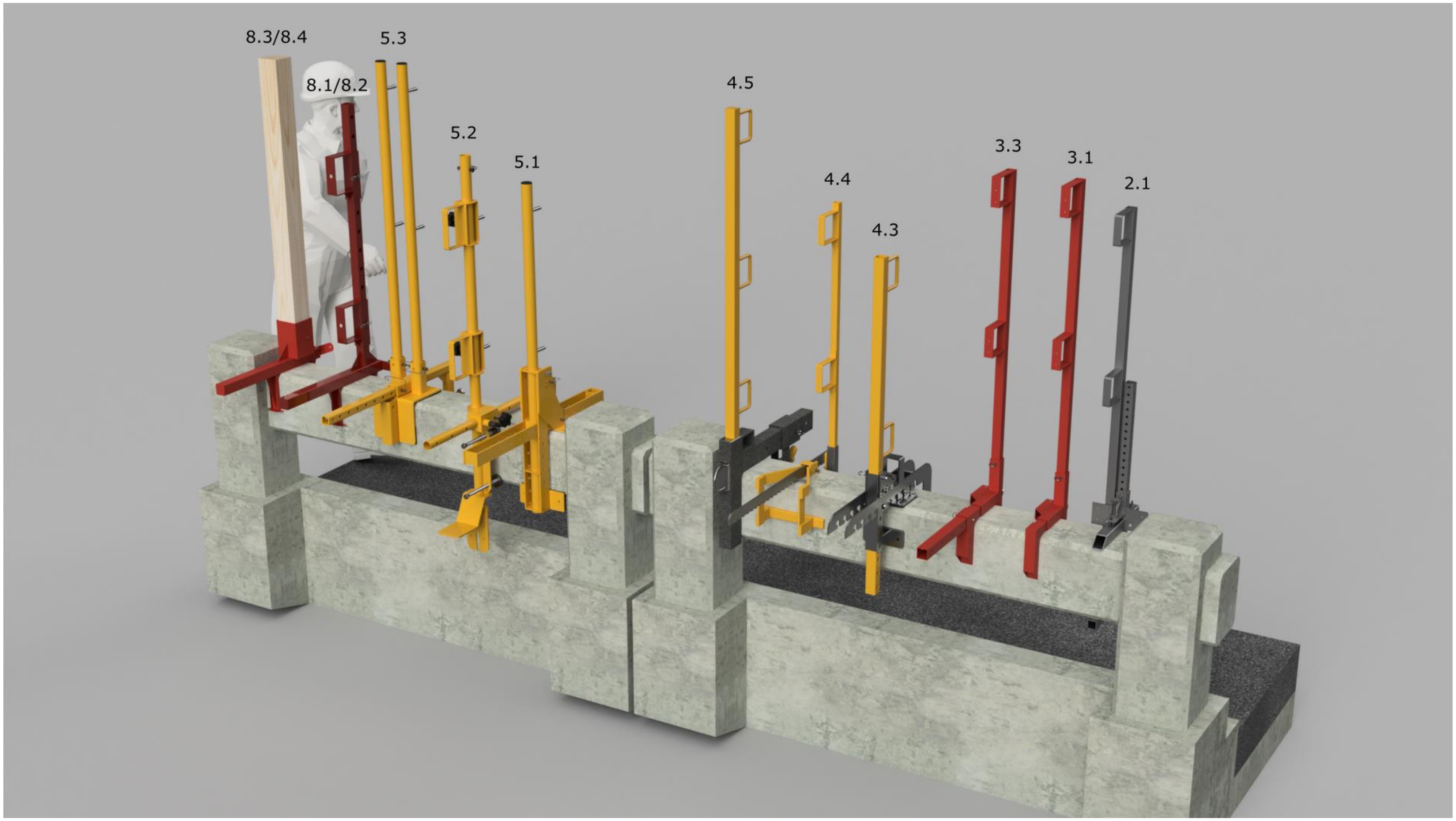


Figure 92 – Guardrail Type 24, variation 2; view from the southwest

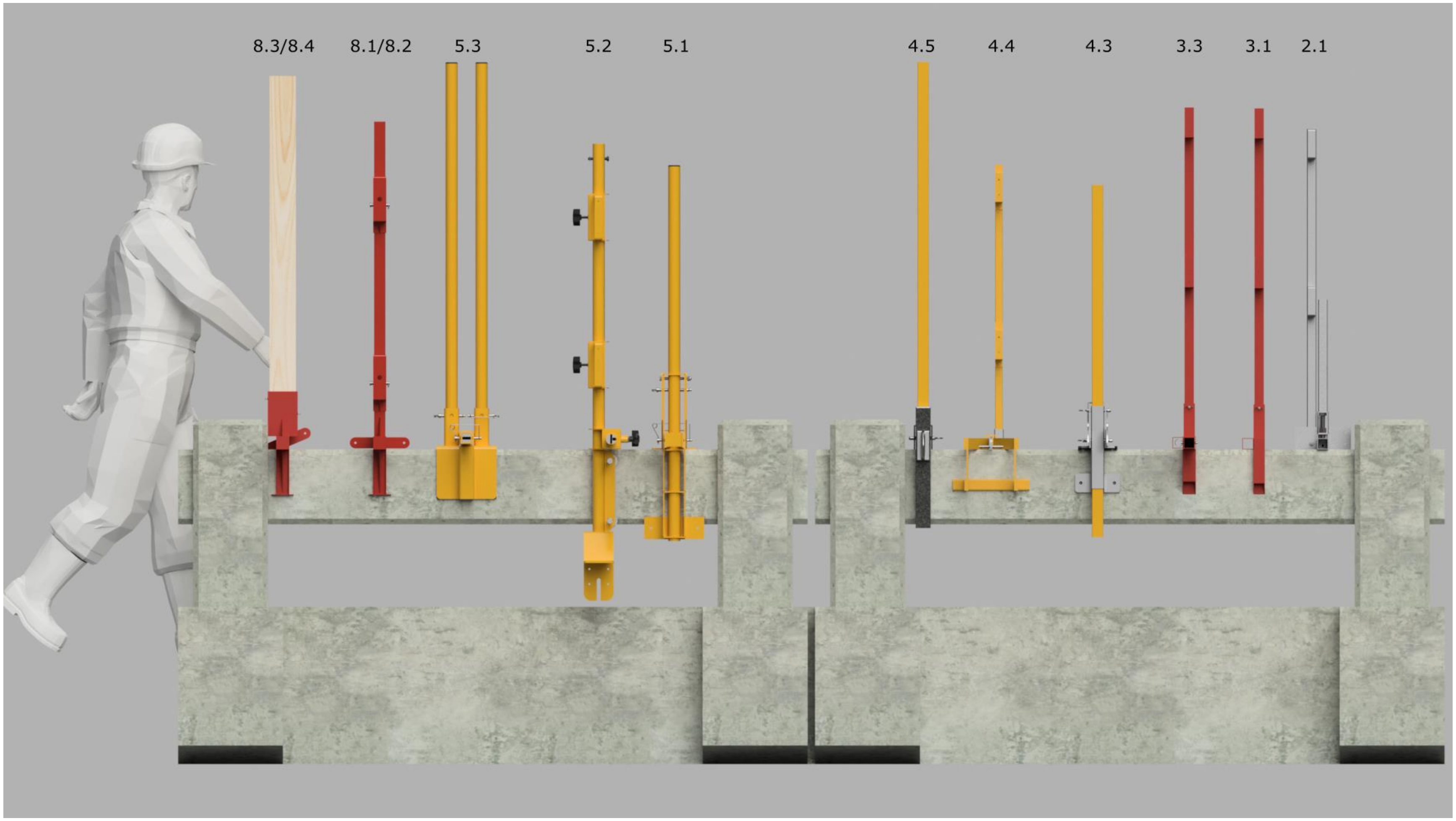


Figure 93 – Guardrail Type 24, variation 2; view from the west

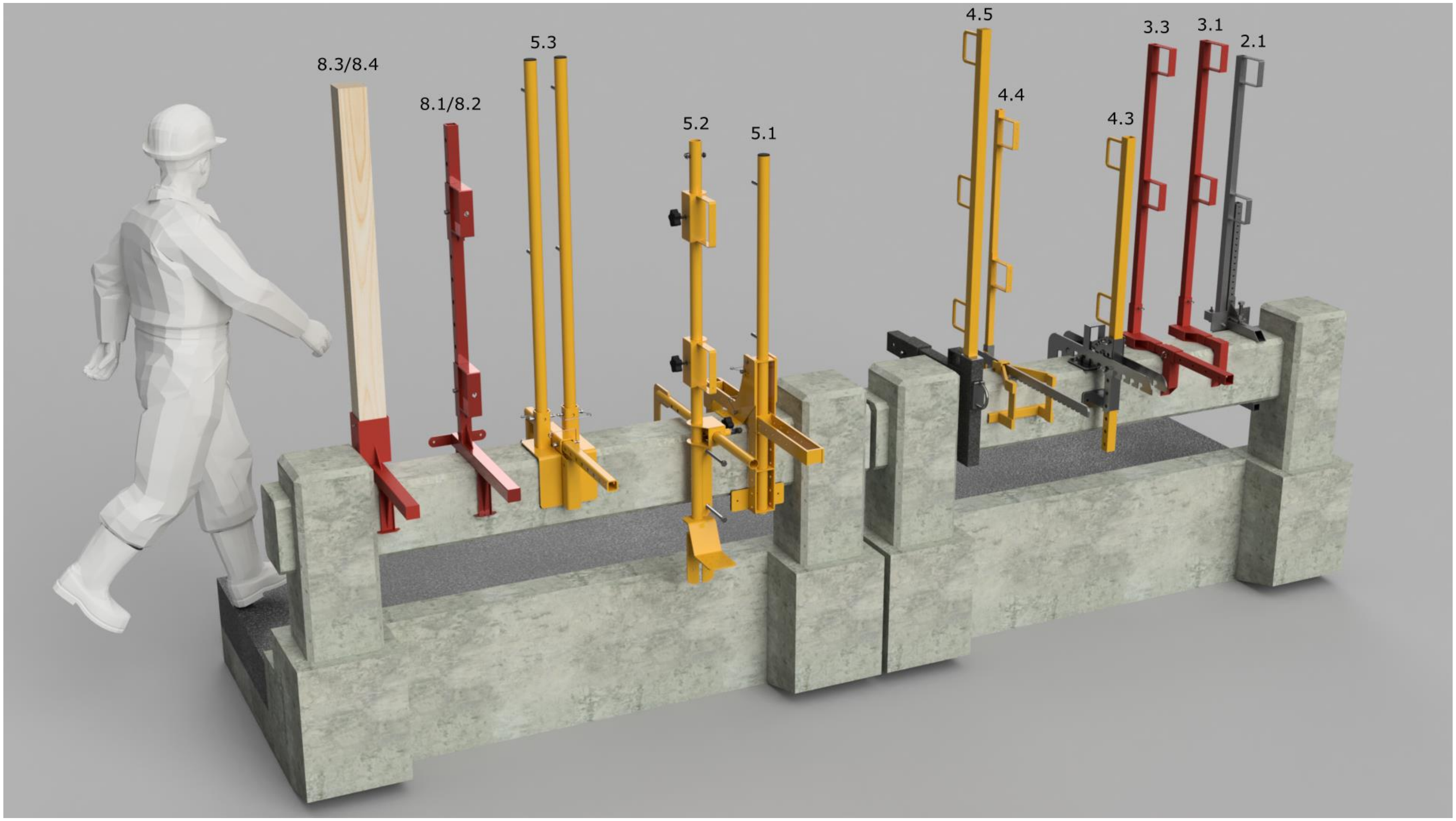


Figure 94 – Guardrail Type 24, variation 2; view from the northwest

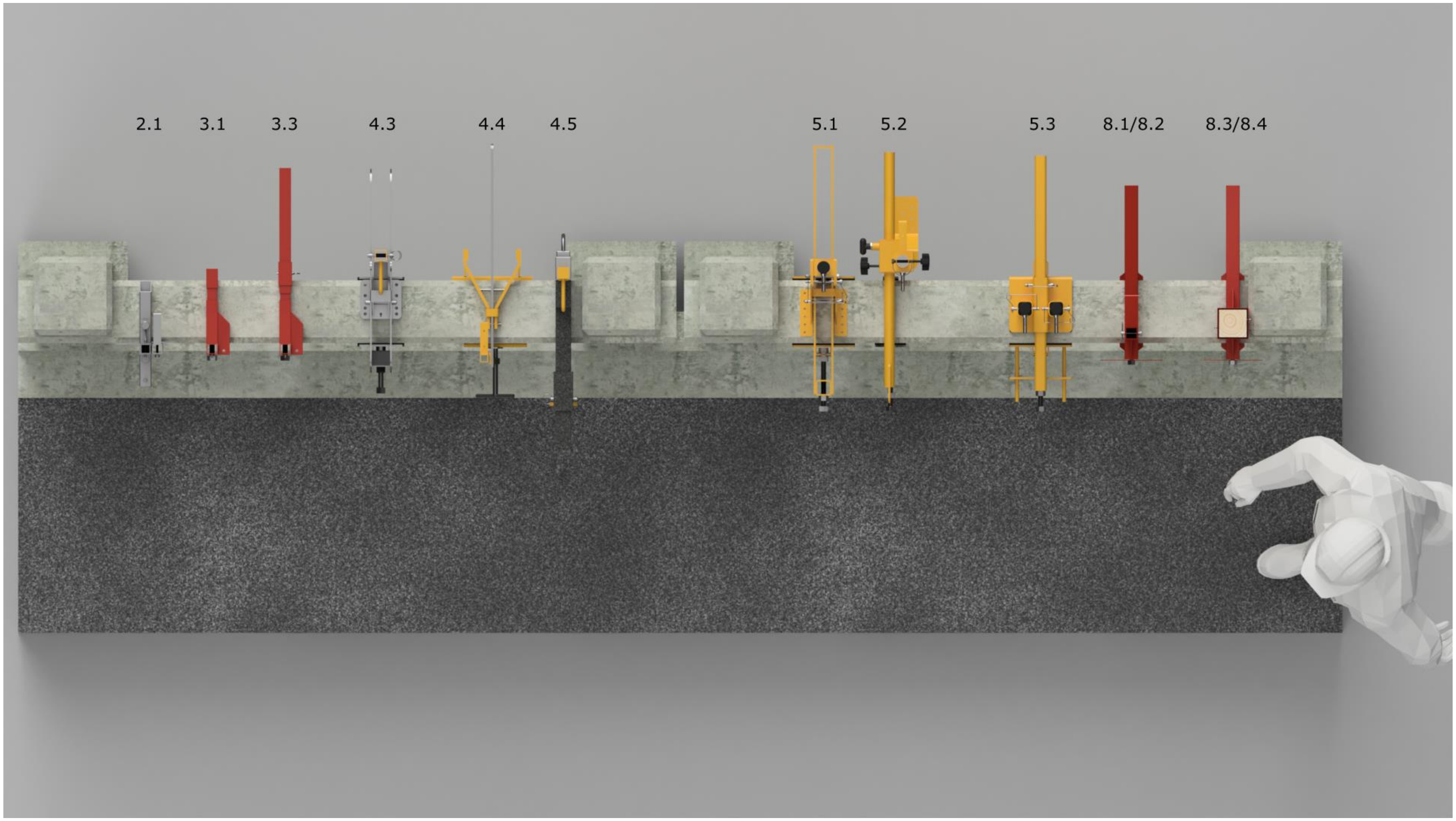


Figure 95 – Guardrail Type 24, variation 2; view from the top

12. GUARDRAIL TYPE 25 – Thrie-Beam

12.1 Description

Guardrail comprised of a horizontal steel section commonly known as "Thrie-beam", bolted to structural steel grade posts. We did not observe a curb or wheel guard in this type railing, but after reviewing Routine Inspection Reports contained in the Wiggins database we did find two variations of the post. The first variation has two W5x15.5 sections behind the Thrie-beam, as shown on Figure 96 and Figure 97. The second variation did not have the shorter W5x15.5 section, and the Thrie beam was bolted to the longer W-section post as shown on Figure 98. We did not perform compatibility testing to verify if the FPSDs would fit on each of the two variations of the post.

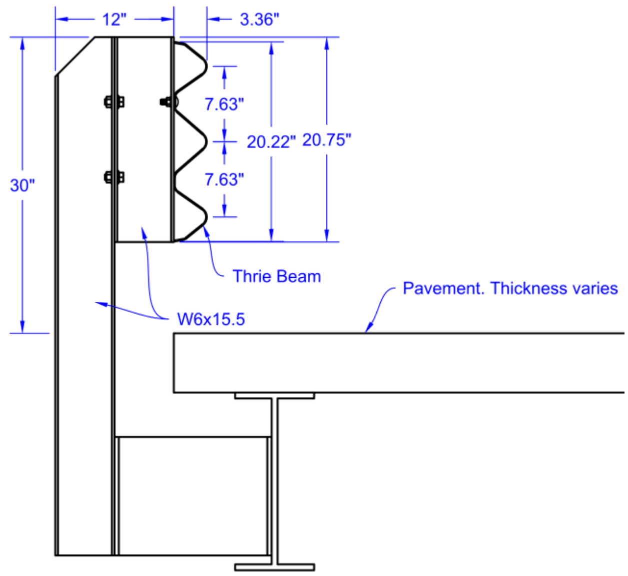


Figure 96 - Guardrail Type 25 section


Figure 97 - Guardrail Type 25, post variation # 1


Figure 98 - Guardrail Type 25, post variation # 2

12.2 Compatibility Chart

Table 10 - Compatibility chart for Guardrail Type 25

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	**Guardrail:** This device fits over the guardrail. A 4"W x 8"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 26.75".
3.1	C-Clamp - CC120	**Guardrail:** This device fits over the guardrail. A 6"W x 8"L lumber piece is needed behind the guardrail. Intrusion into the work area is approximately 2.25".
3.3	Master C-Clamp - MCC130	**Guardrail:** This device fits over the guardrail. A 6"W x 8"L lumber piece is needed behind the guardrail. Intrusion into the work area is approximately 2.25".
4.3	Alligator Parapet Guardrail system - 15167	**Guardrail:** The device fits over the guardrail. 2"W x 8"L lumber pieces are needed; one in front of the guardrail and one in the back of the guardrail. Intrusion into the work area is approximately 8".
4.4	Parapet Clamp Guardrail System - 15170	**Guardrail:** The device fits over the guardrail. 2"W x 8"L lumber pieces are needed; one in front of the guardrail and one in the back of the guardrail. Intrusion into the work area is approximately 8.5".
4.5	Parapet Anchor - 15171	**Guardrail:** This device fits over the guardrail. A 2"W x 8"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 17.5".
5.1	RaptorRail	**Guardrail:** This device fits over the guardrail. Intrusion into the work area is approximately 8.75".
5.2	All-In-One	**Guardrail:** This device fits over the guardrail in two ways. First, the device is clamped only to the Thrie-beam. One 2"W x 8"L lumber piece is needed behind the guardrail. In the second and preferred fit, the lower part of the device is supported on the deck. Then the adjusting arm clamps to the Thrie beam. In both cases, Intrusion into the work area is approximately 8.5".
5.3	Universal Guardrail Parapet Clamp	**Guardrail:** This device fits over the guardrail. A 2"W x 8"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 10.5".
8.1	Parapet Guardrails GRS-P12	**Guardrail:** This device fits over the guardrail. A 2"W x 8"L lumber piece is needed in front of the guardrail. The tightening handle faces the inside of the bridge. Intrusion into the work area is approximately 5.25".
8.2	Parapet Guardrails GRS-P24	**Guardrail:** This device fits over the guardrail. A 2"W x 8"L lumber piece is needed in front of the guardrail. The tightening handle faces the inside of the bridge. Intrusion into the work area is approximately 5.25".
8.3	QuickRail Parapet Guardrail QR-P12	**Guardrail:** This device fits over the guardrail. A 2"W x 8"L lumber piece is needed in front of the guardrail. The tightening handle faces the inside of the bridge. Intrusion into the work area is approximately 4.25".
8.4	QuickRail Parapet Guardrail QR-P24	**Guardrail:** This device fits over the guardrail. A 2"W x 8"L lumber piece is needed in front of the guardrail. The tightening handle faces the inside of the bridge. Intrusion into the work area is approximately 4.25".

12.3 Renderings

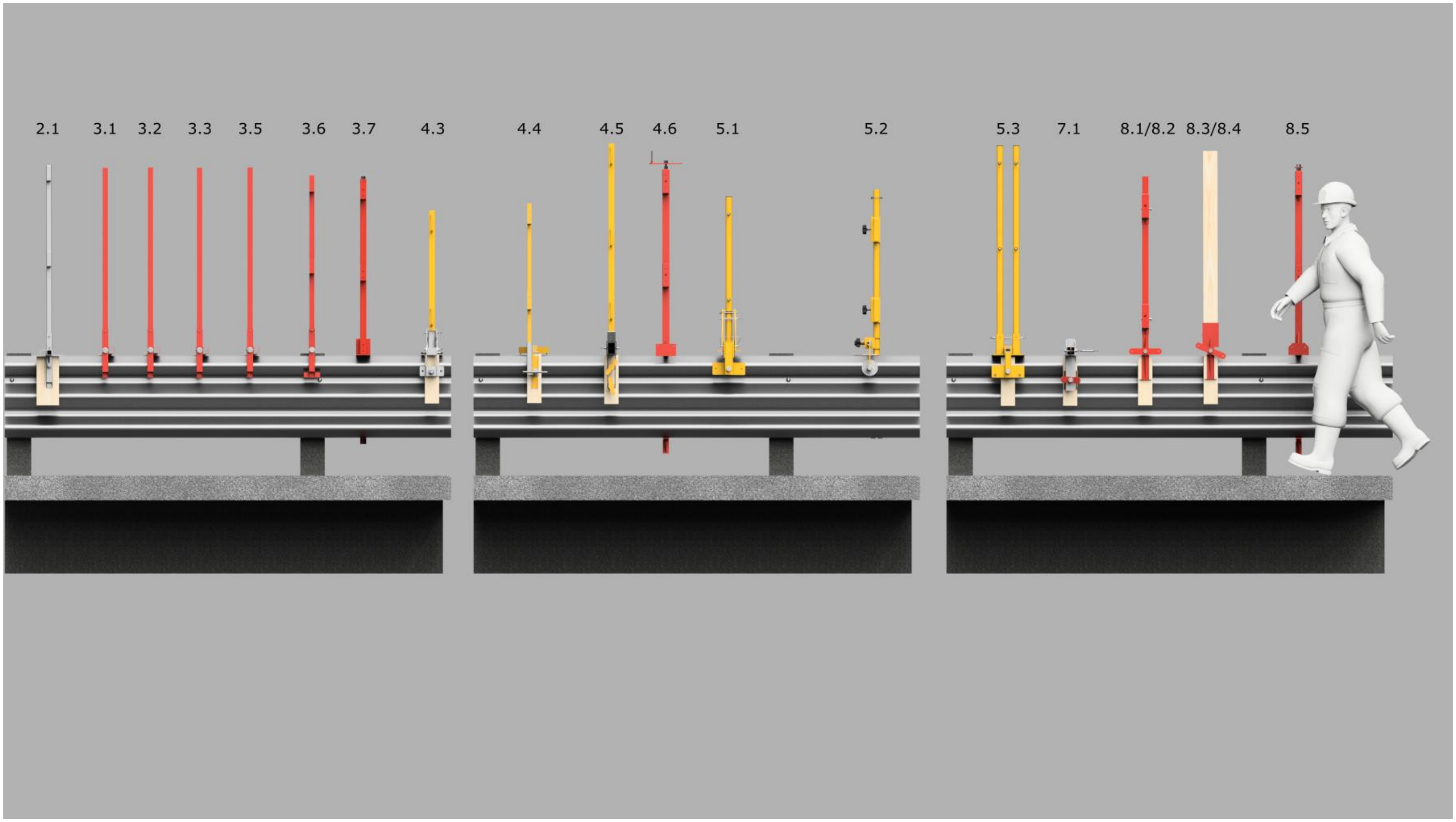


Figure 99 - Guardrail Type 25; view from the east

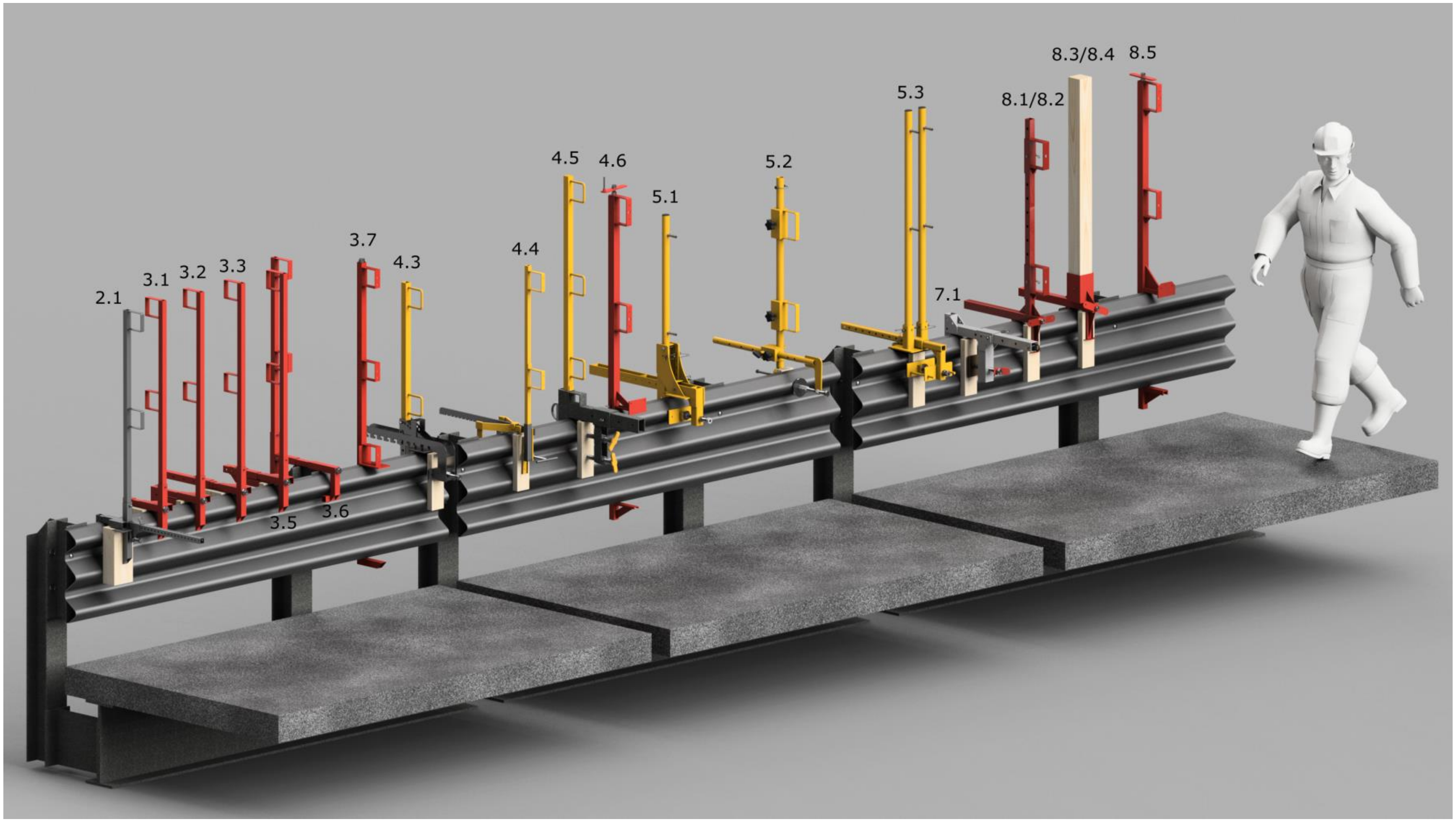


Figure 100 - Guardrail Type 25; view from the southeast

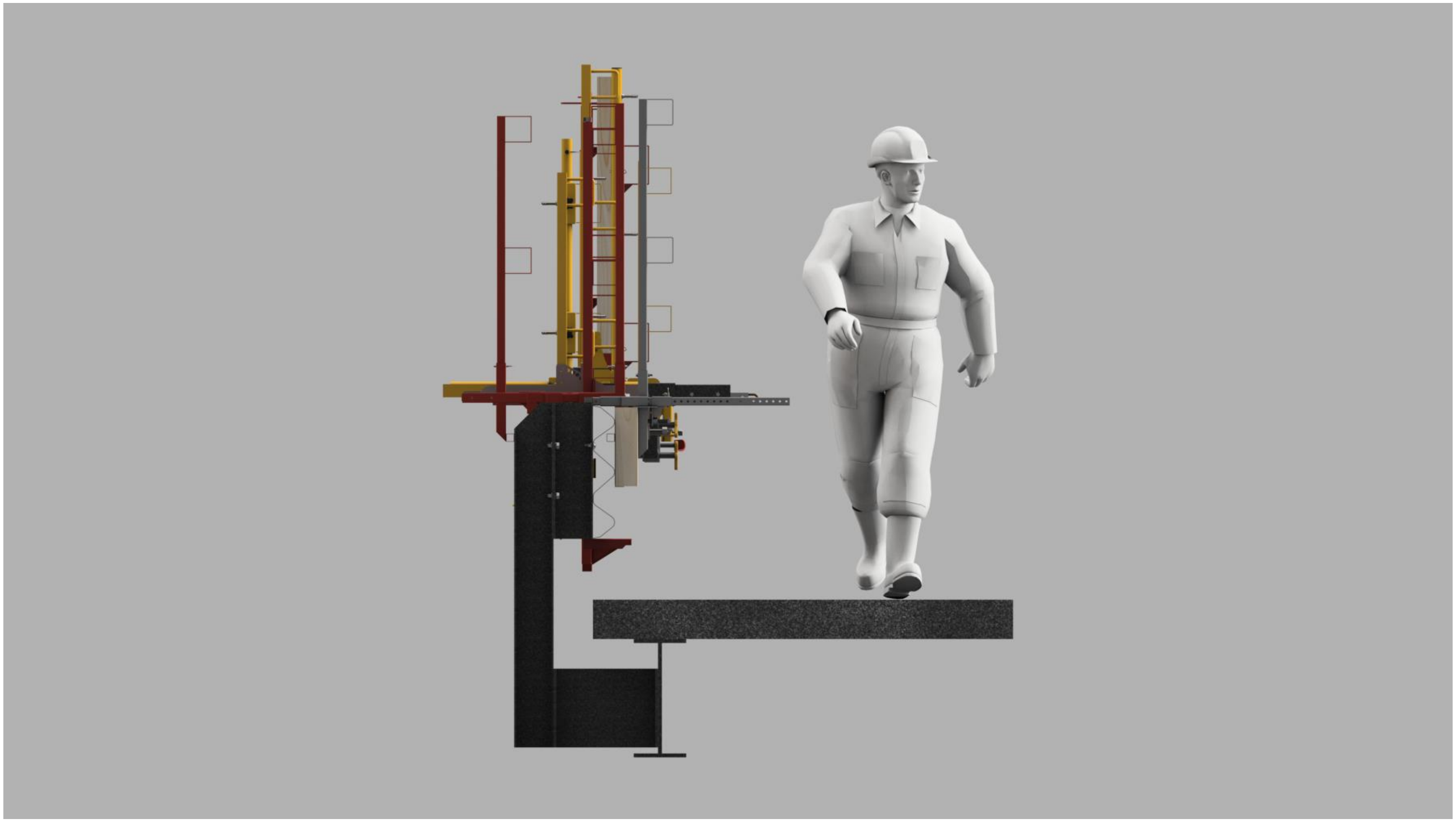


Figure 101 - Guardrail Type 25; view from the south

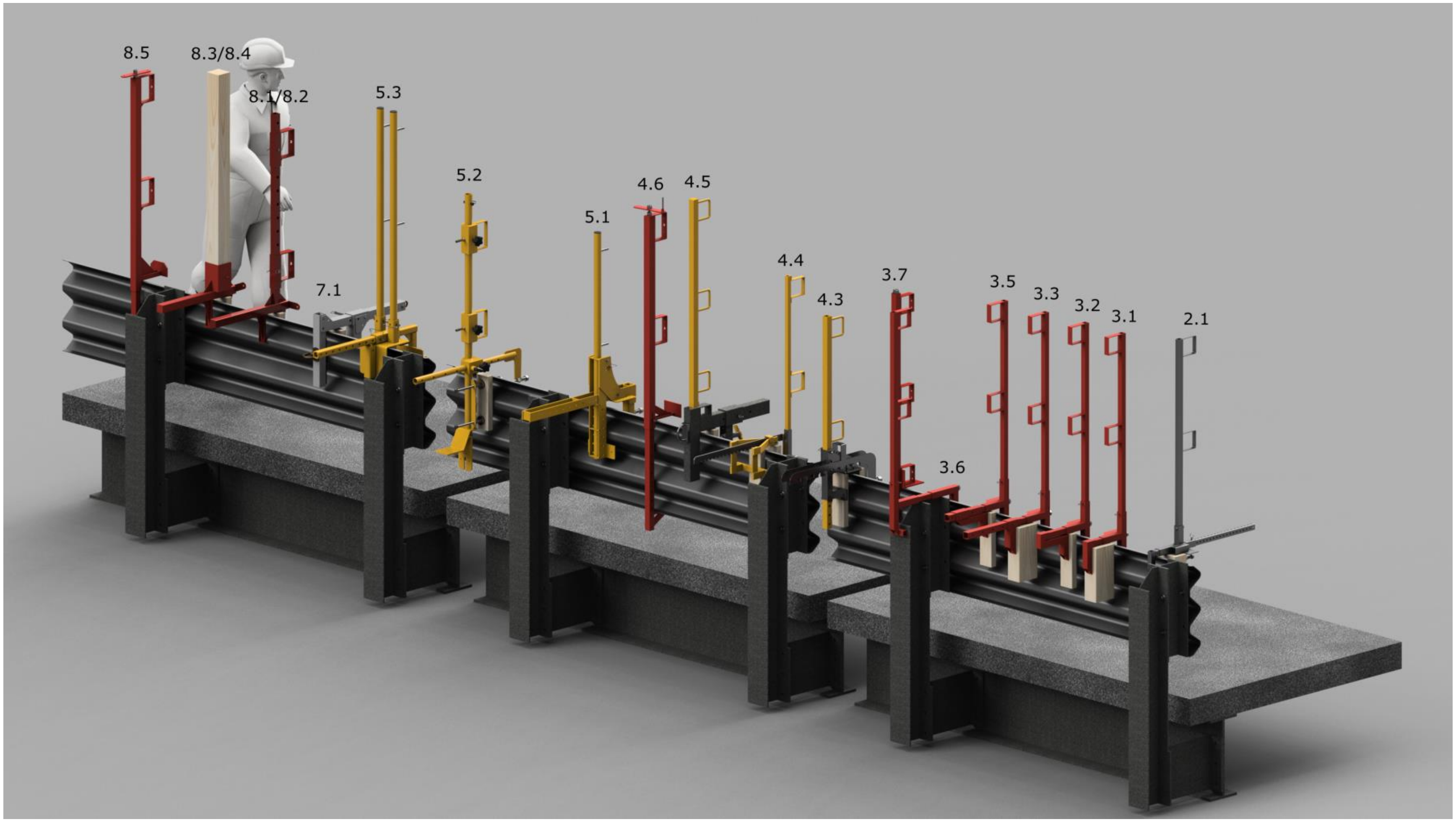


Figure 102 - Guardrail Type 25; view from the southwest

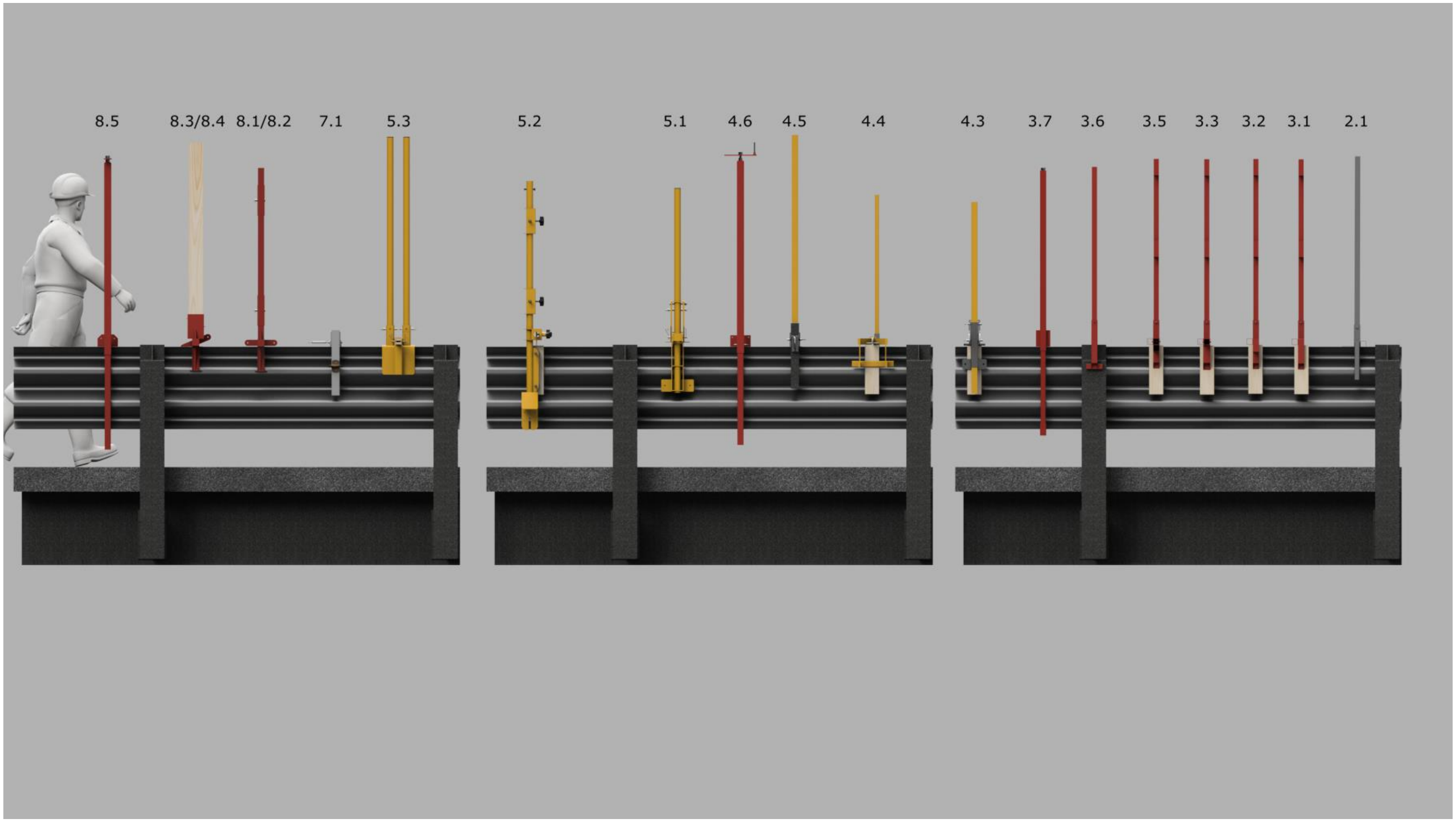


Figure 103 - Guardrail Type 25; view from the west

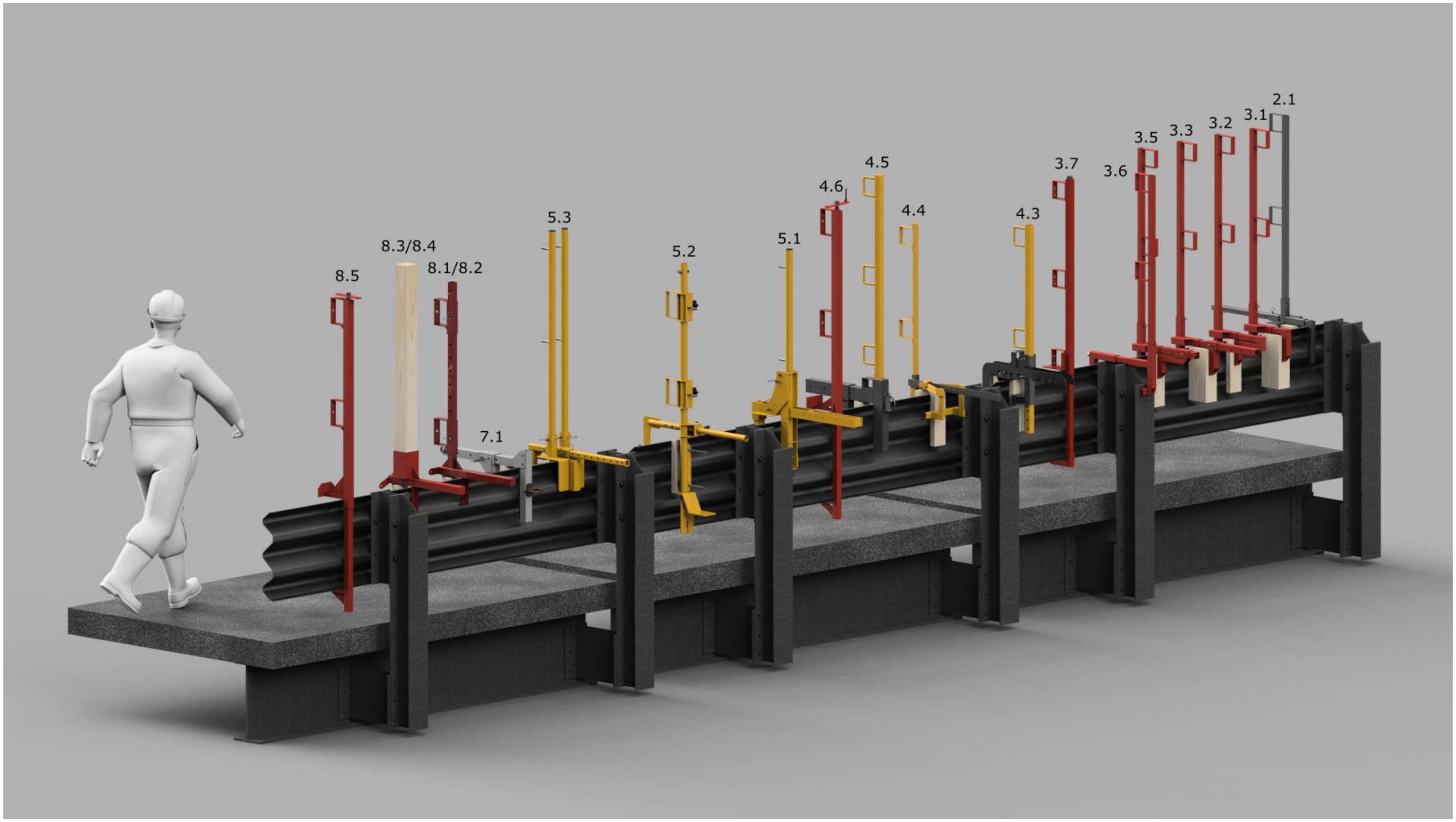


Figure 104 - Guardrail Type 25; view from the northwest

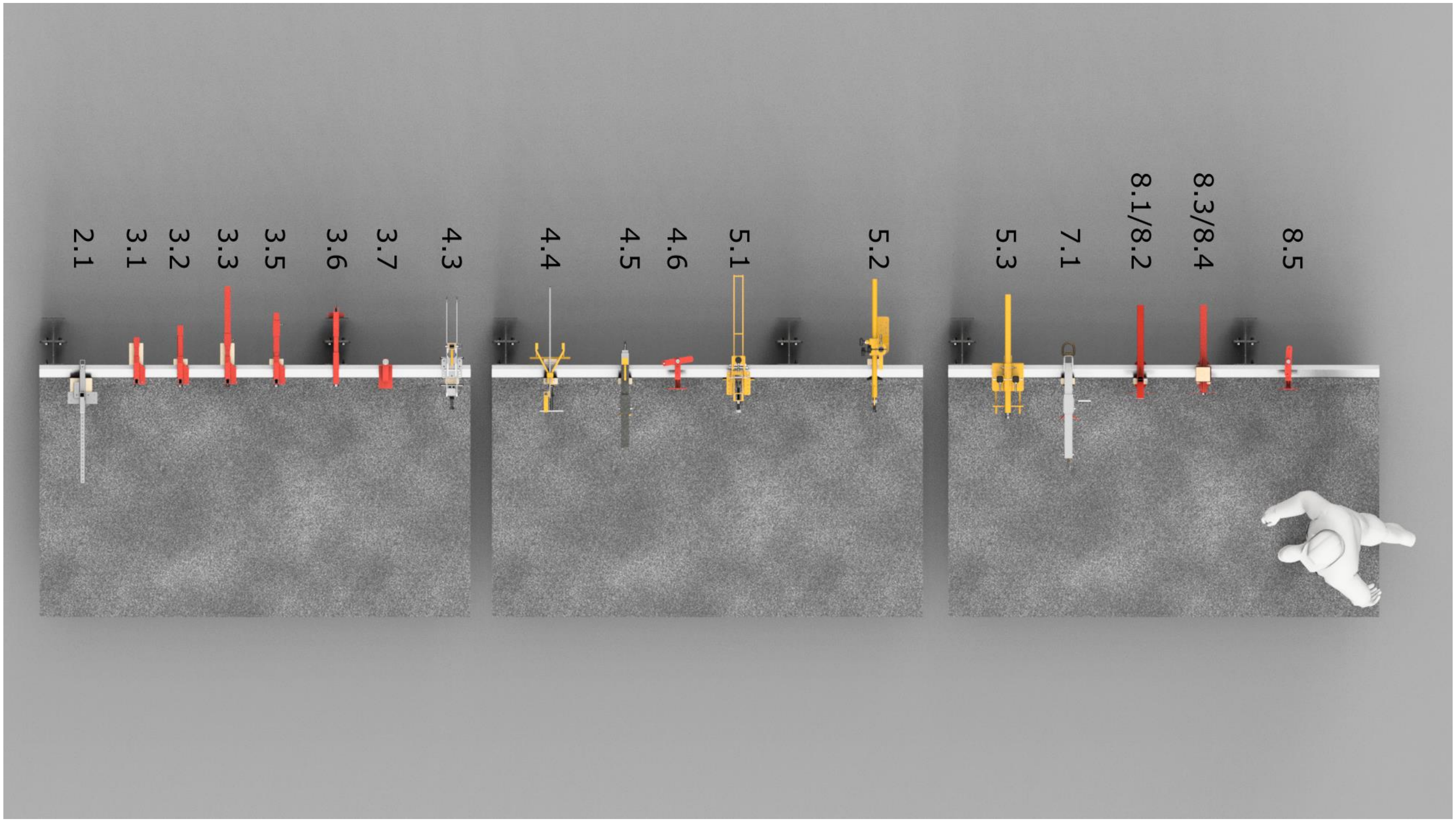


Figure 105 - Guardrail Type 25; view from the top

13. GUARDRAIL TYPE 31 – Concrete Church Window

13.1 Description

Commonly referred to as "Church Window", this guardrail comprised of vertical reinforced concrete sections with elliptical openings equally spaced between reinforced concrete end posts.

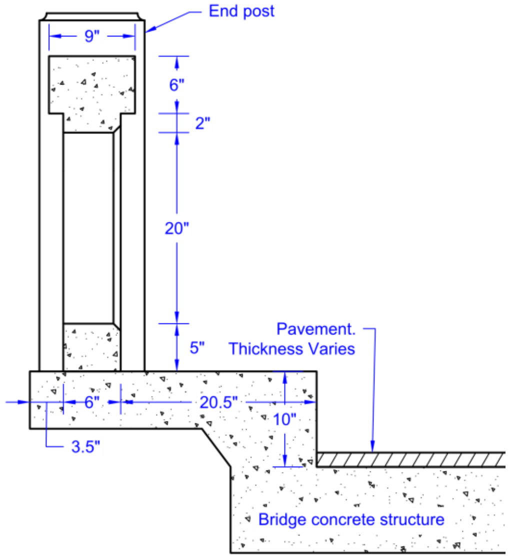


Figure 106 – Guardrail Type 31 section

13.2 Compatibility Chart

Table 11 – Compatibility chart for Guardrail Type 31

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the concrete rail as either slab clamp or parapet clamp. Model is shown as slab clamp as it intrudes the least into the work area (approximately 5.5").
3.1	C-Clamp - CC120	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.25"
3.3	Master C-Clamp - MCC130	The device fits over the concrete rail as either slab clamp or parapet clamp. Model is shown as parapet clamp as offers the most convenient installation. Intrusion into the work area approximately 2.25".
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 6.5"
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 7"
4.5	Parapet Anchor - 15171	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 12"
5.1	RaptorRail	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75"
5.2	All-In-One	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75"
5.3	Universal Guardrail Parapet Clamp	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75"
8.1	Parapet Guardrails GRS-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75"

ID	PRODUCT NAME	COMPATIBILITY NOTES
8.2	Parapet Guardrails GRS-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.3	QuickRail Parapet Guardrail QR-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.4	QuickRail Parapet Guardrail QR-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”

13.3 Renderings

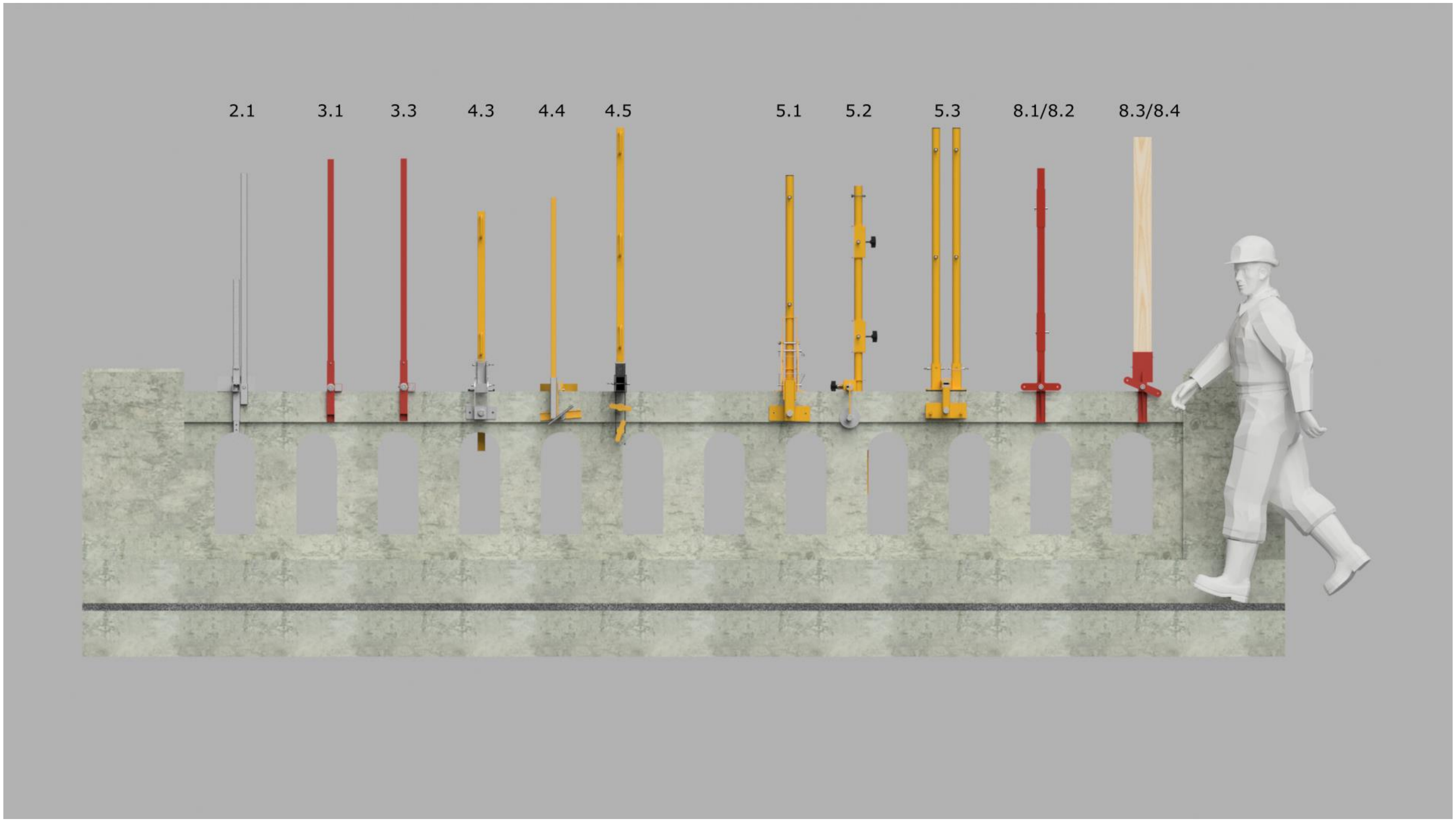


Figure 107 – Guardrail Type 31; view from the east

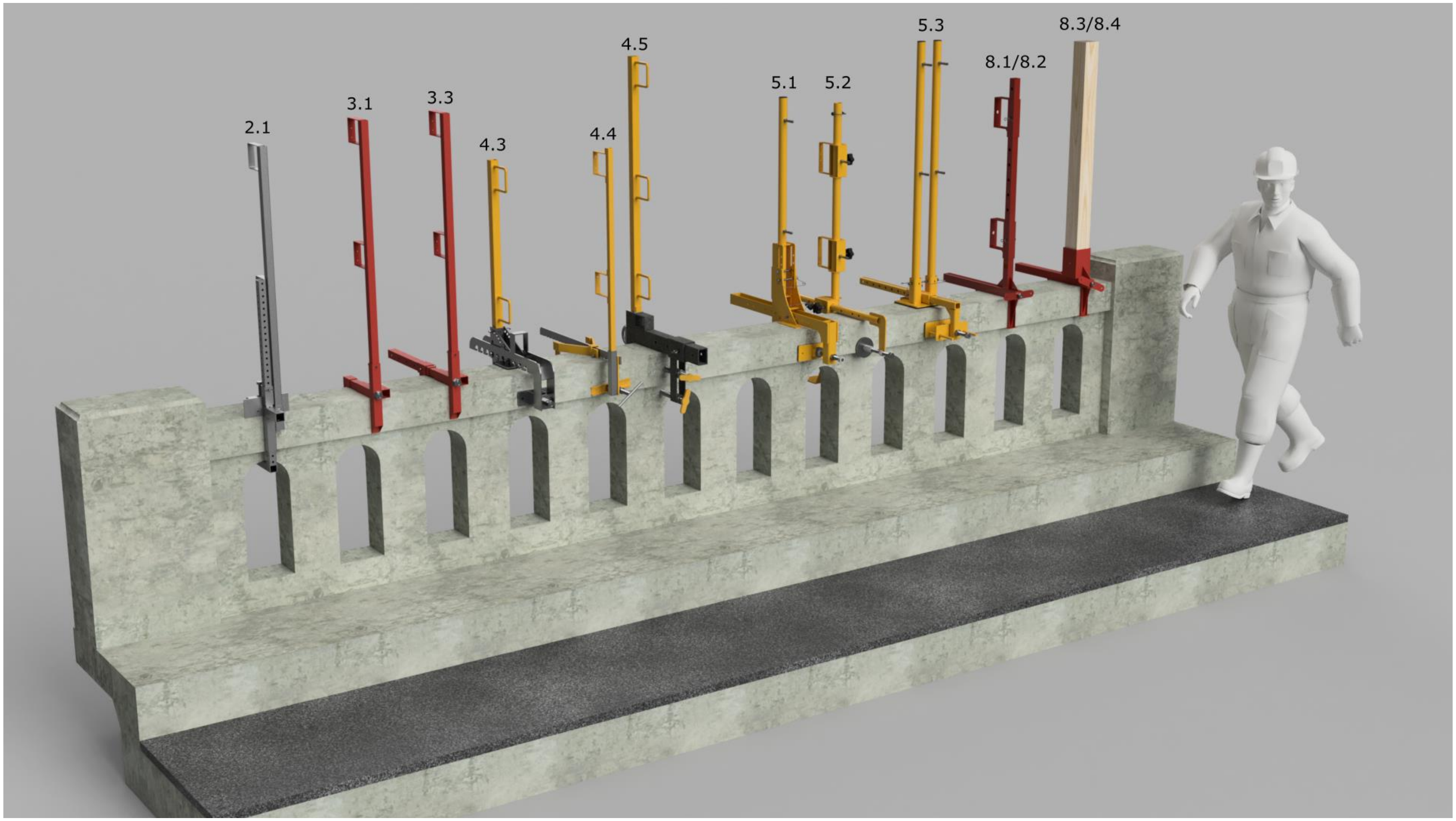


Figure 108 – Guardrail Type 31; view from the southeast

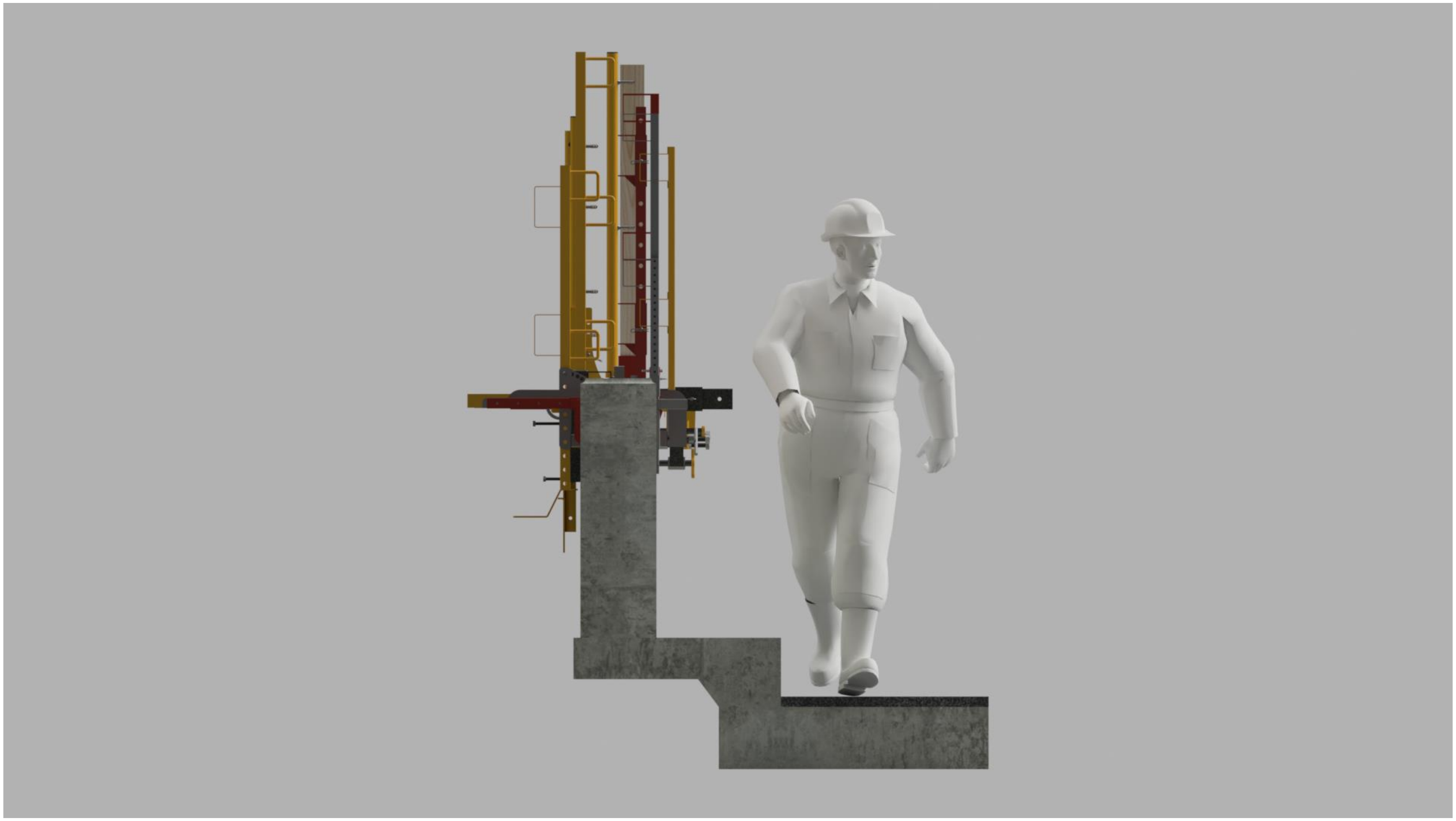


Figure 109 – Guardrail Type 31; view from the south

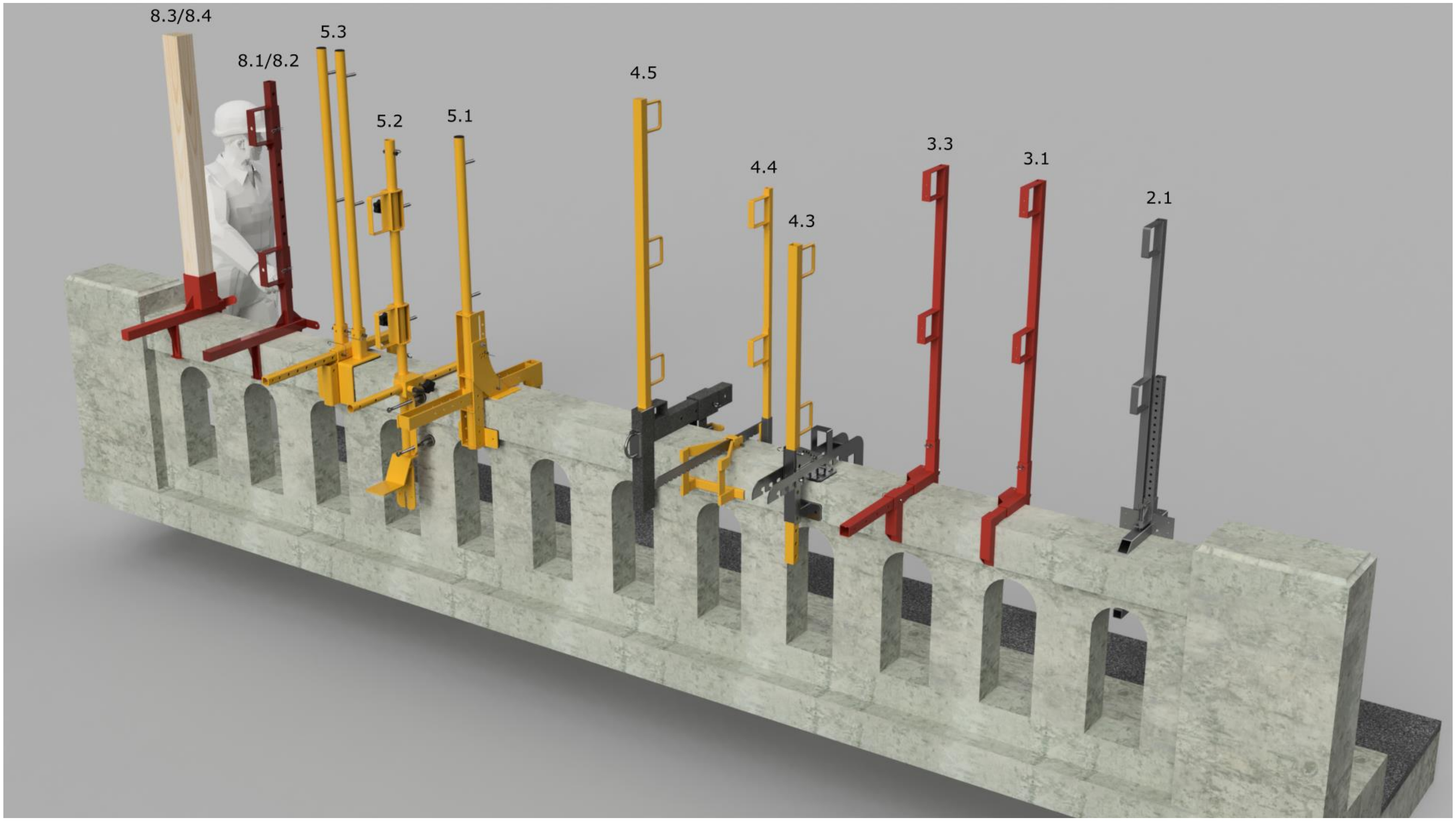


Figure 110 – Guardrail Type 31; view from the southwest

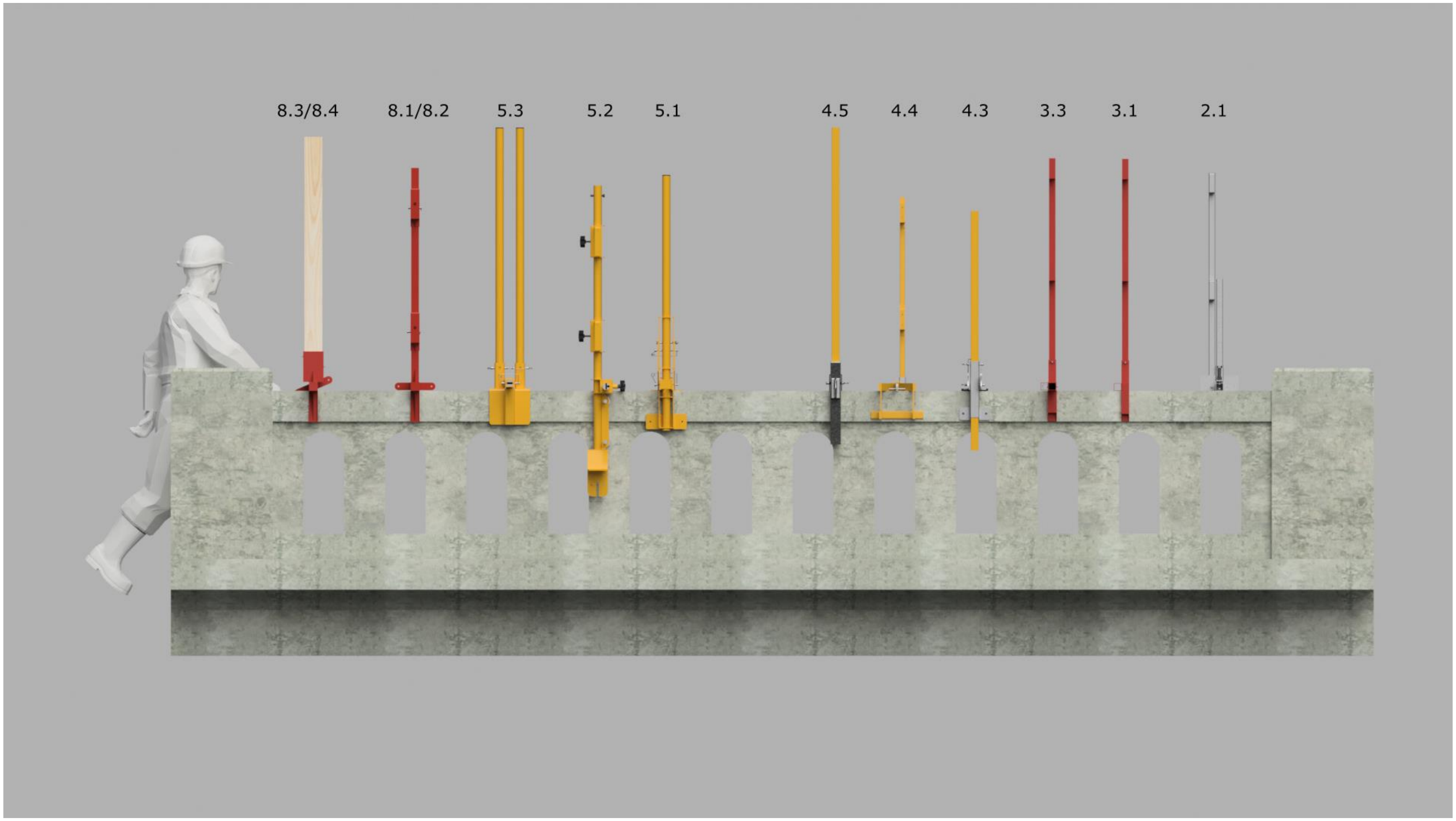


Figure 111 – Guardrail Type 31; view from the west

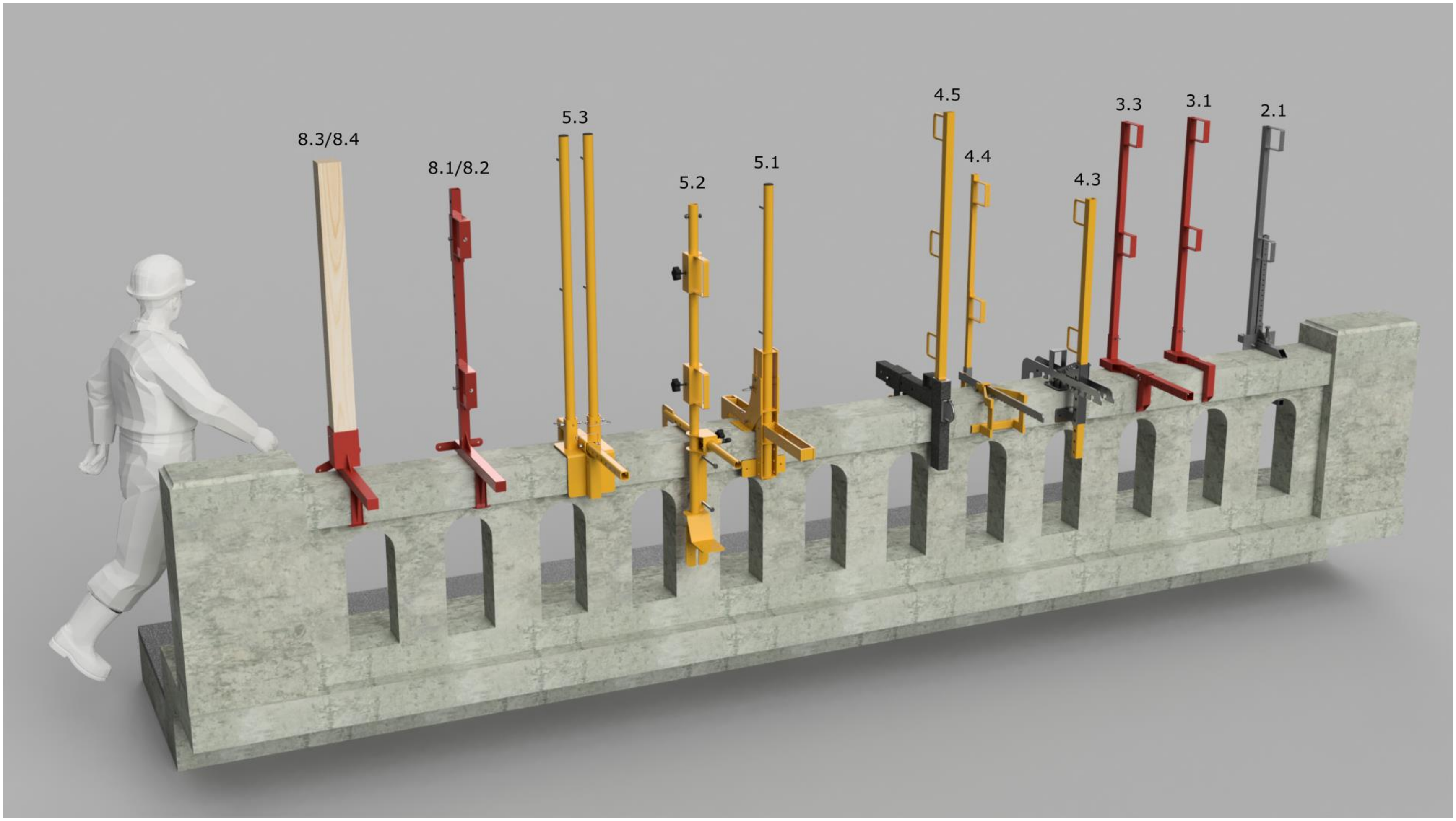


Figure 112 – Guardrail Type 31; view from the northwest

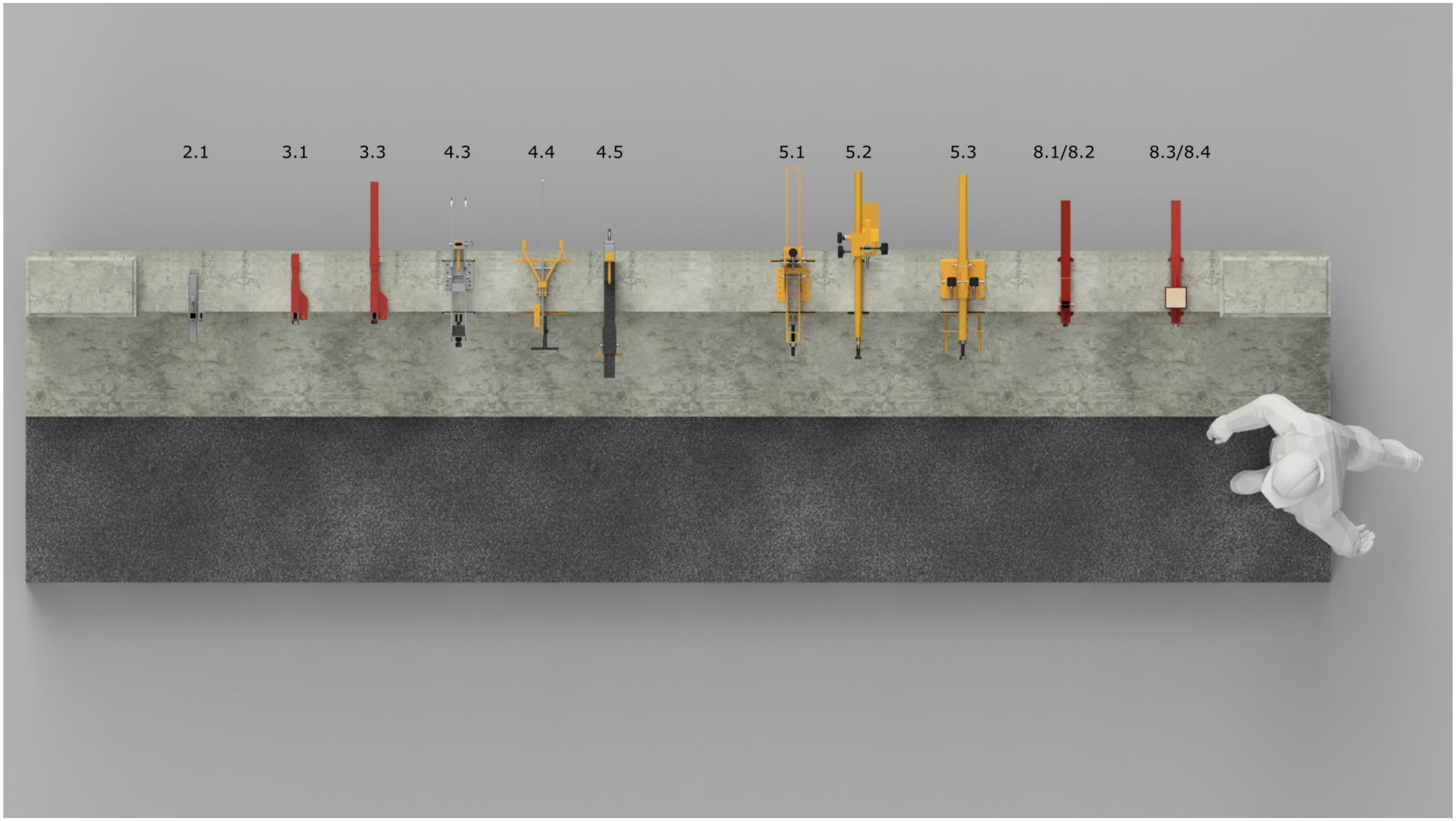


Figure 113 – Guardrail Type 31; view from the top

14. GUARDRAIL TYPE 32 – Tubular Thrie-Beam

14.1 Description

Guardrail comprised of a horizontal steel section commonly known as "Tubular Thrie-beam", bolted to structural steel grade posts. Much of characteristics of this guardrail are very similar to GUARDRAIL TYPE 25 – Thrie-Beam, specifically the posts and attachment to the bridge structure. The difference is that the steel section for Type 32 is tubular, that is, two single thrie-beams opposing each other as the horizontal steel section. Contrary to Guardrail Type 25, we did not observe for this guardrail a curb or wheelguard that allows the installation of the FPSDs.

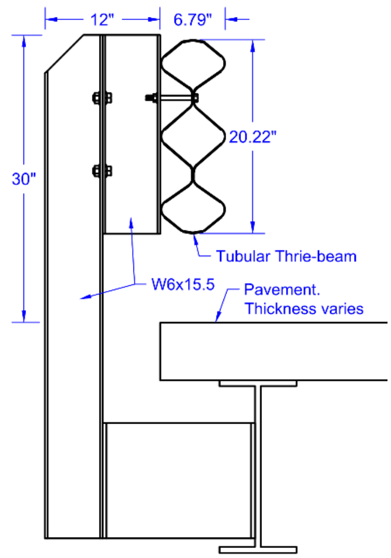


Figure 114 – Guardrail Type 32 section

14.2 Compatibility Chart

Table 12 – Compatibility chart for Guardrail Type 32

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the guardrail as either slab clamp or parapet clamp. However, as slab clamp, the FPSD does not provide enough contact area between the FPSD and the rail, possibly being an unsafe installation. Therefore, the model is shown as parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 23.25"
3.1	C-Clamp - CC120	This device fits over the guardrail as parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 3.75"
3.3	Master C-Clamp - MCC130	The device fits over the guardrail as either slab clamp or parapet clamp. However, as slab clamp, the FPSD does not provide enough contact area between the FPSD and the rail, possibly being an unsafe installation. Therefore, the model is shown as parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 3.75"
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the guardrail as parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 8"

ID	PRODUCT NAME	COMPATIBILITY NOTES
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the guardrail as parapet clamp. 2”W x 12”L lumber is needed at front and back of the guardrail. Intrusion into the work area is approximately 8.25”
4.5	Parapet Anchor - 15171	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 12”
5.1	RaptorRail	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75”
5.2	All-In-One	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75”
5.3	Universal Guardrail Parapet Clamp	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.75”
8.1	Parapet Guardrails GRS-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.2	Parapet Guardrails GRS-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.3	QuickRail Parapet Guardrail QR-P12	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”
8.4	QuickRail Parapet Guardrail QR-P24	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 2.75”

14.3 Renderings

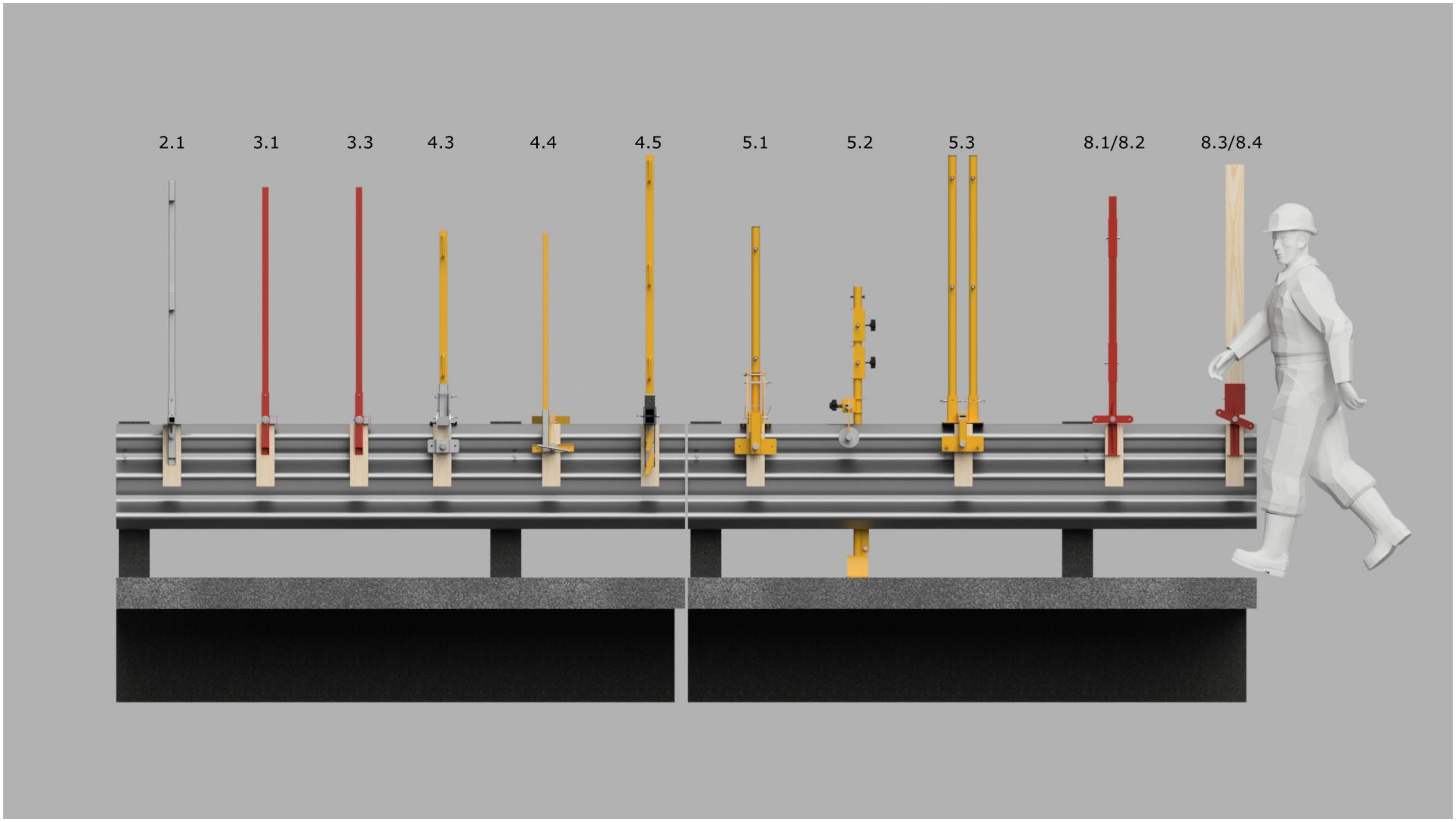


Figure 115 – Guardrail Type 32; view from the east

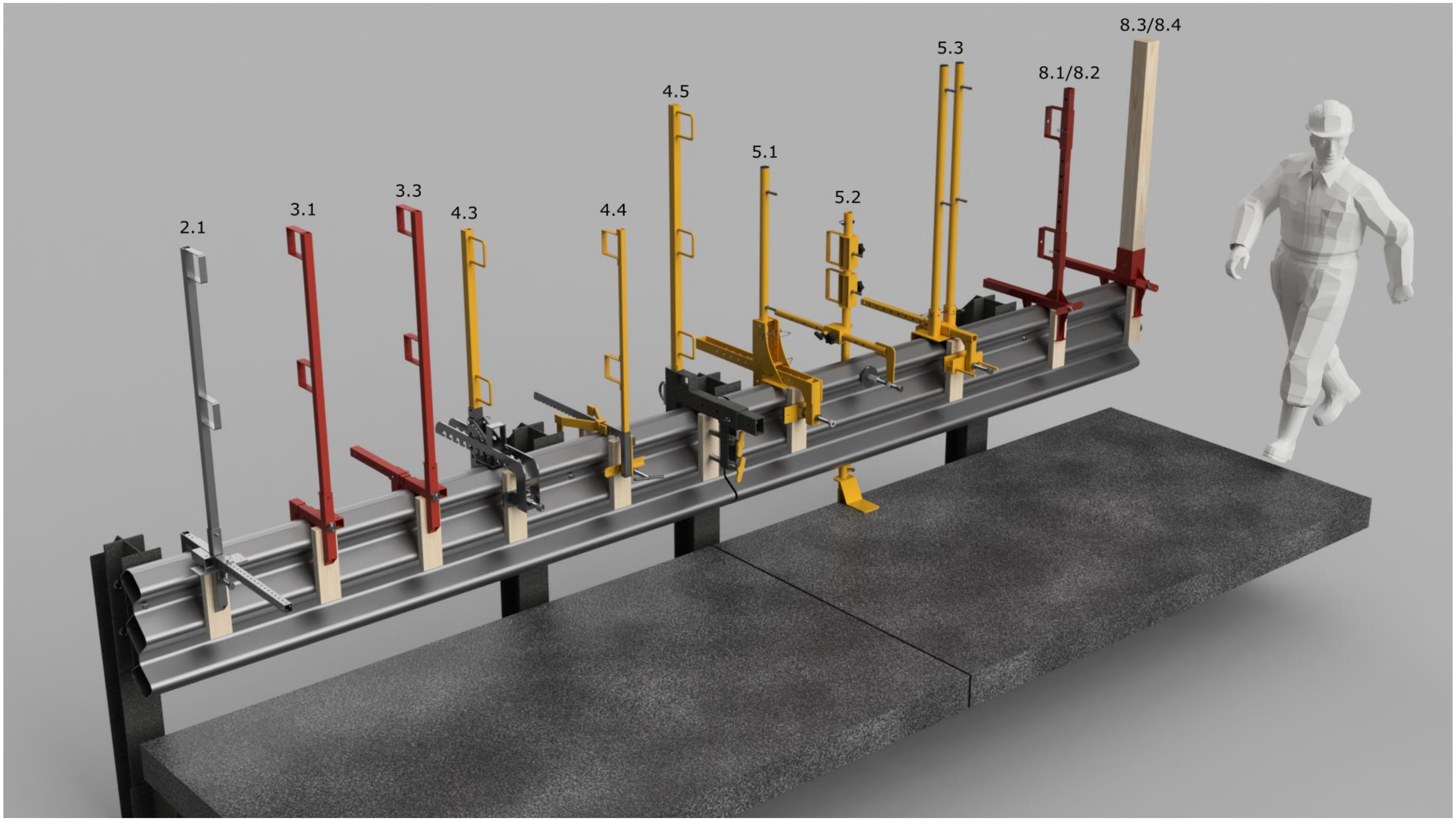


Figure 116 – Guardrail Type 32; view from the southeast

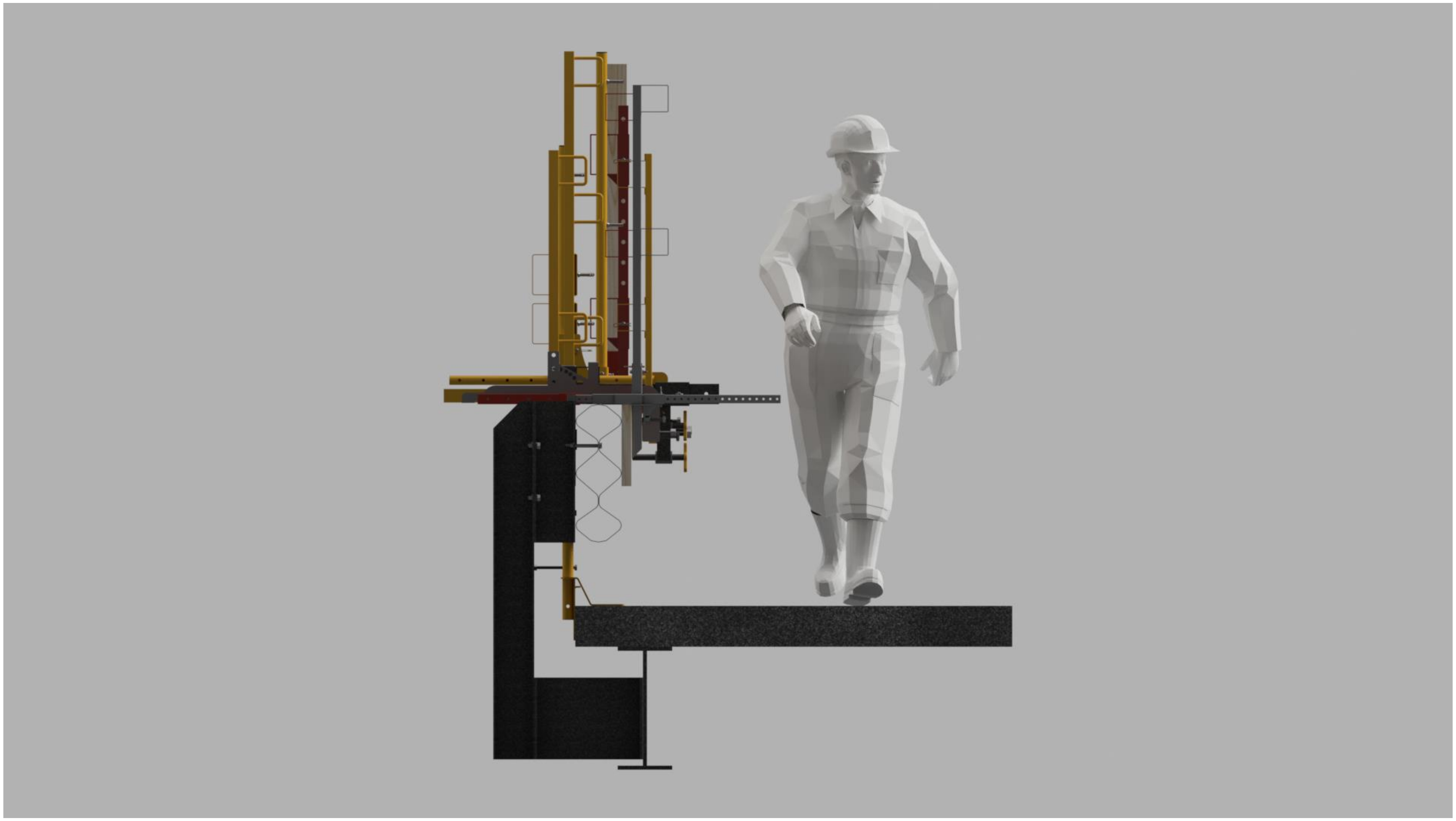


Figure 117 – Guardrail Type 32; view from the south

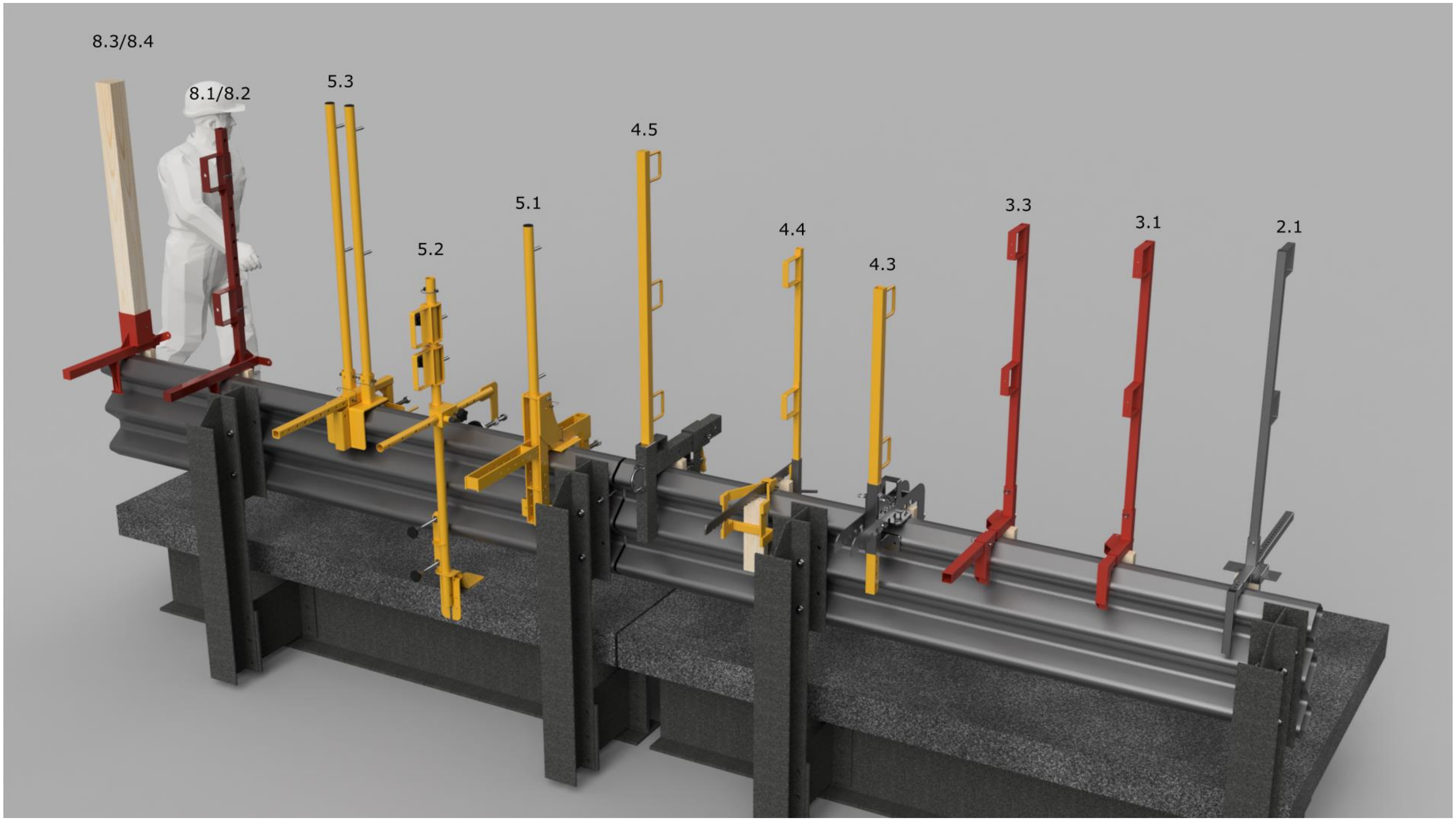


Figure 118 – Guardrail Type 32; view from the southwest

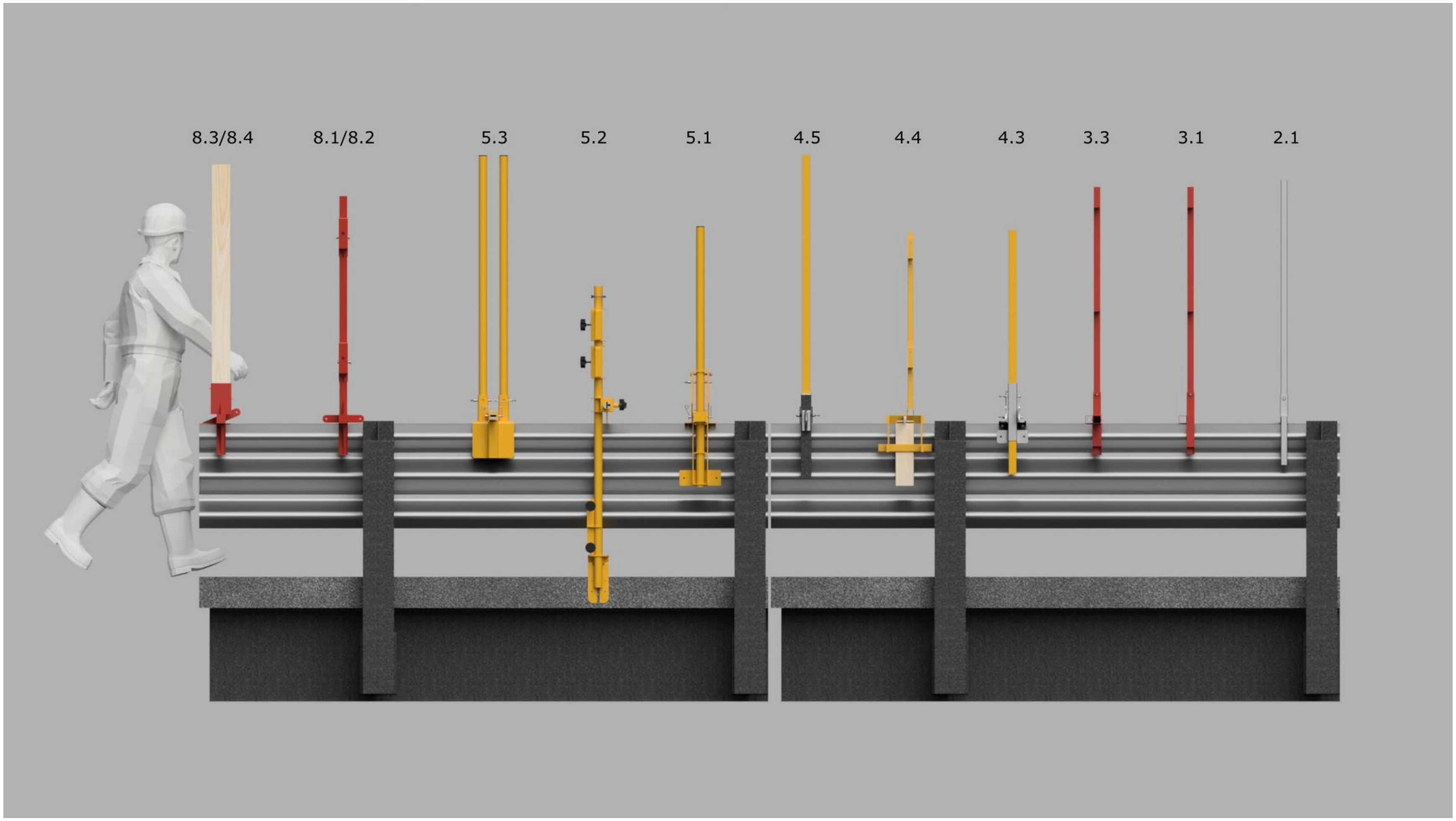


Figure 119 – Guardrail Type 32; view from the west

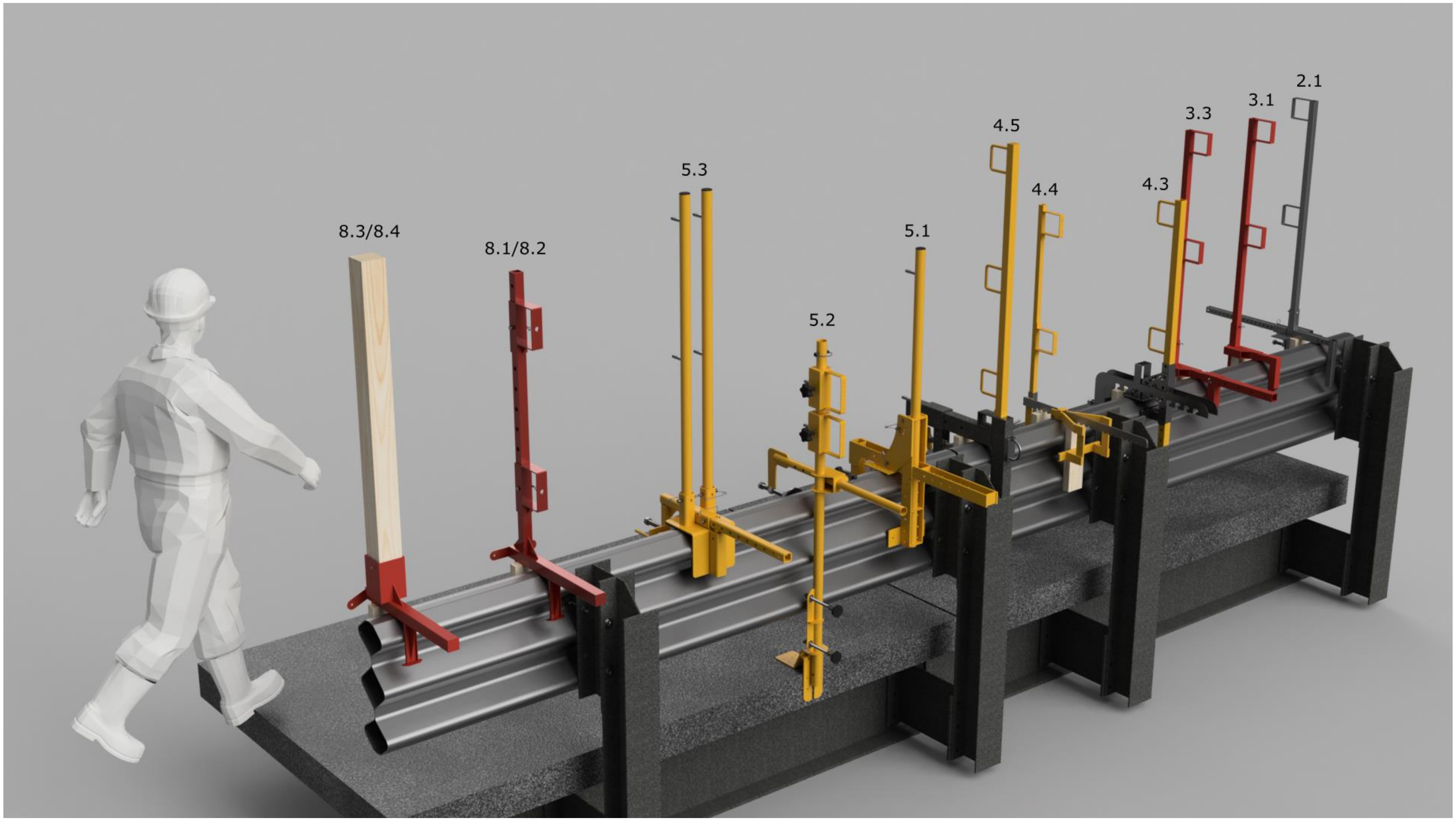


Figure 120 – Guardrail Type 32; view from the northwest

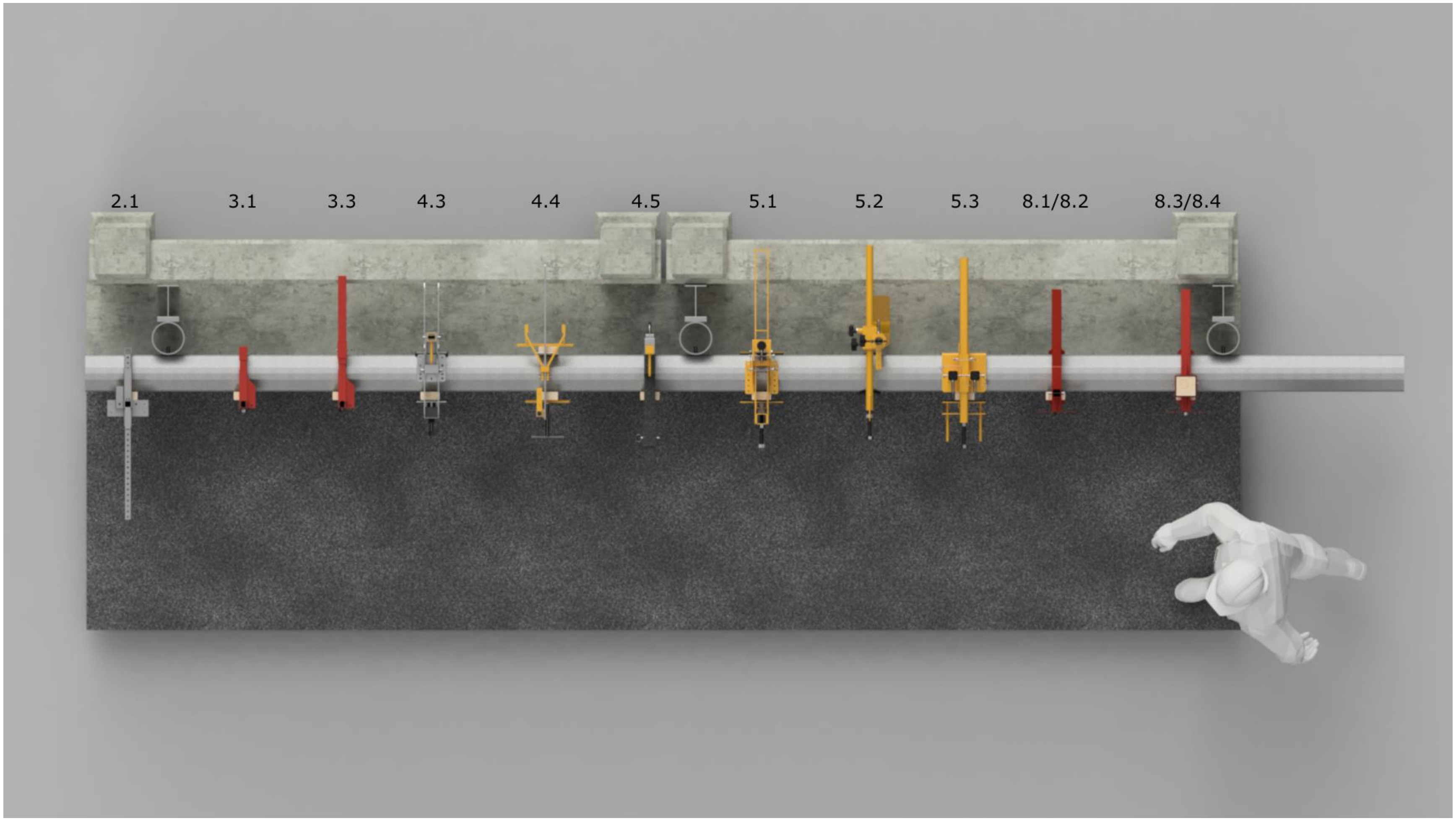


Figure 121 – Guardrail Type 32; view from the top

15. GUARDRAIL TYPE 33 – Tubular Thrie-Beam Retrofit

15.1 Description

This guardrail type is a typical retrofit to concrete 1-bar guardrails such as Guardrail Type 11 that are prone to snagging and vaulting of vehicles. To solve prevent snagging and vaulting, a retrofit using tubular thrie-beam sections is placed in front of the existing guardrail. Compatibility testing was performed on the tubular thrie-beam because of the convenient installation. However, installation is also possible on the concrete 1-bar guardrail.

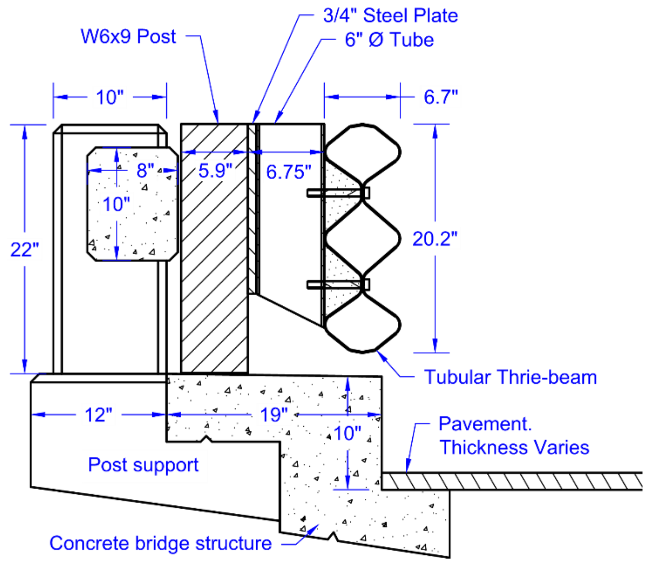


Figure 122 – Guardrail Type 33 section

15.2 Compatibility Chart

Table 13 – Compatibility chart for Guardrail Type 33

ID	PRODUCT NAME	COMPATIBILITY NOTES
2.1	Flexiguard Portable Guardrail	The device fits over the guardrail as a parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 23.25"
3.1	C-Clamp - CC120	This device fits over the guardrail as parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 3.75"
3.3	Master C-Clamp - MCC130	The device fits over the guardrail as either slab clamp or parapet clamp. However, as slab clamp, the FPSD does not provide enough contact area between the FPSD and the rail, possibly being an unsafe installation. Therefore, the model is shown as parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 3.75"
4.3	Alligator Parapet Guardrail system - 15167	This device fits over the guardrail as parapet clamp. A 2"W x 12"L lumber piece is needed in front of the guardrail. Intrusion into the work area is approximately 8"

ID	PRODUCT NAME	COMPATIBILITY NOTES
4.4	Parapet Clamp Guardrail System - 15170	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 8.25”
4.5	Parapet Anchor - 15171	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 14.25”
5.1	RaptorRail	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 10.25”
5.2	All-In-One	This device fits over the concrete rail as parapet clamp. Intrusion into the work area is 8.5”
5.3	Universal Guardrail Parapet Clamp	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 10.25”
8.1	Parapet Guardrails GRS-P12	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 4.25”
8.2	Parapet Guardrails GRS-P24	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 4.25”
8.3	QuickRail Parapet Guardrail QR-P12	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 4.25”
8.4	QuickRail Parapet Guardrail QR-P24	This device fits over the guardrail as parapet clamp. A 2”W x 12”L lumber piece is needed at front and back of the guardrail. Intrusion into the work area is approximately 4.25”

15.3 Renderings

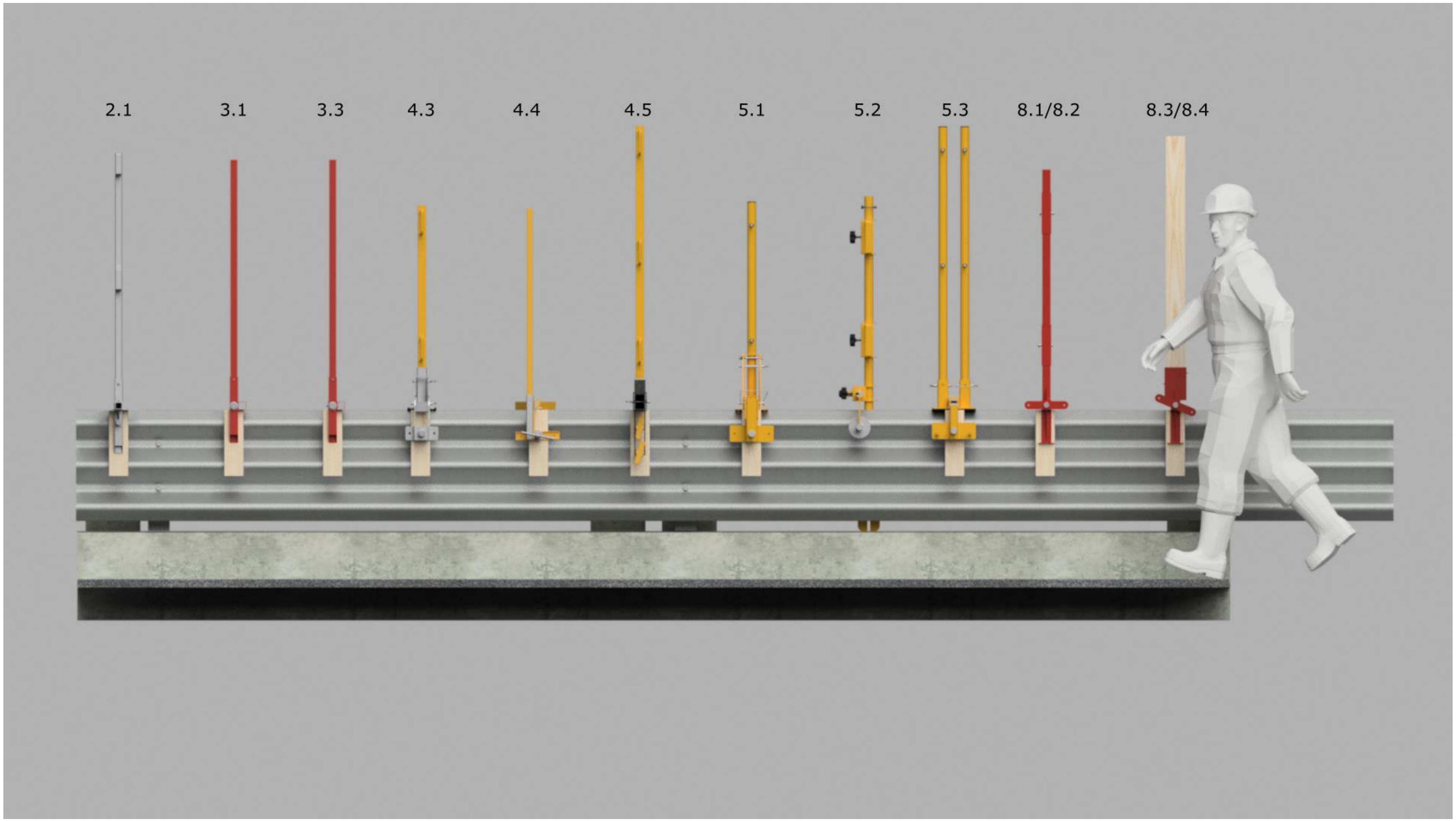


Figure 123 – Guardrail Type 33; view from the east

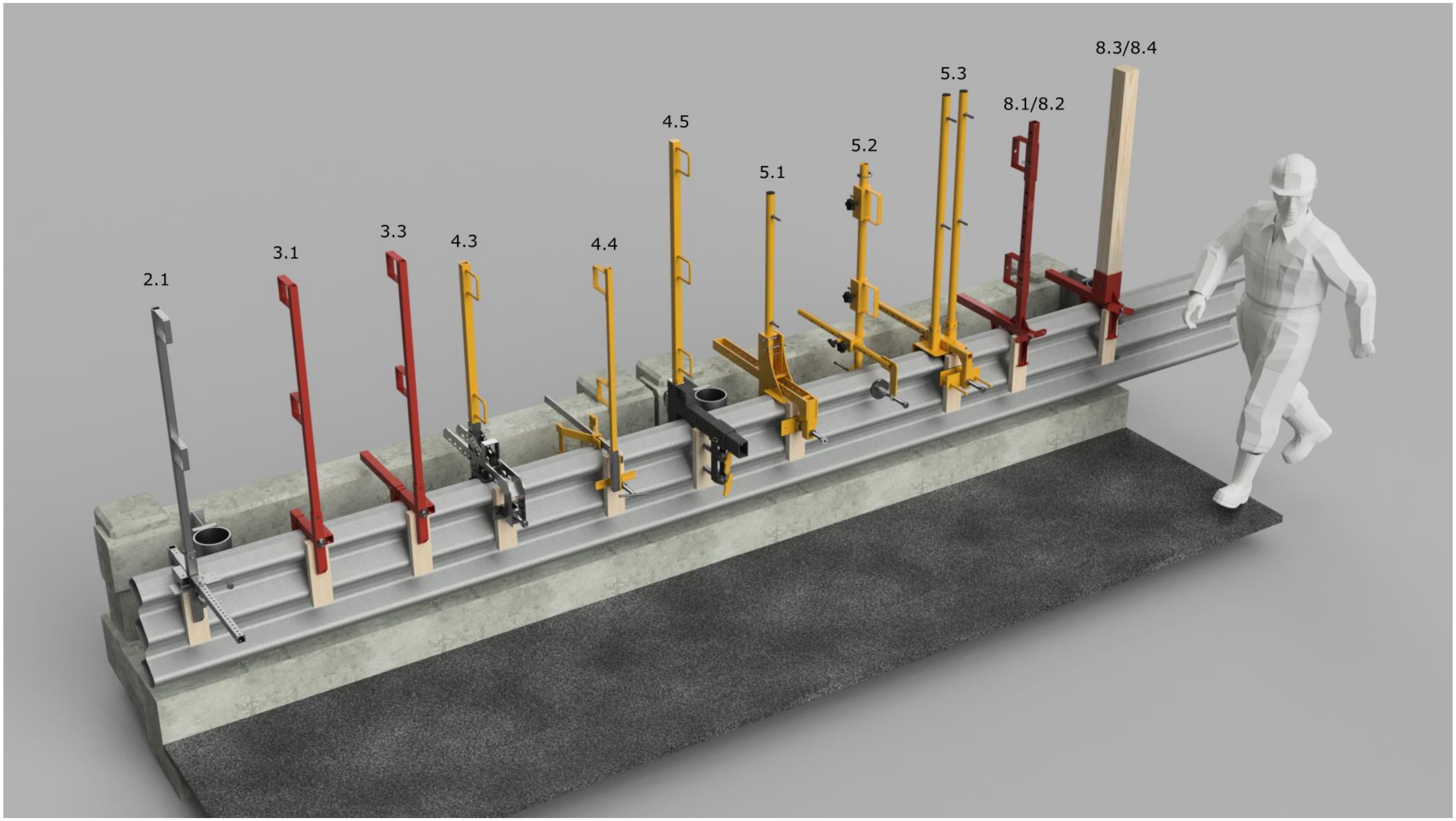


Figure 124 – Guardrail Type 33; view from the southeast

Figure 125 – Guardrail Type 33; view from the south

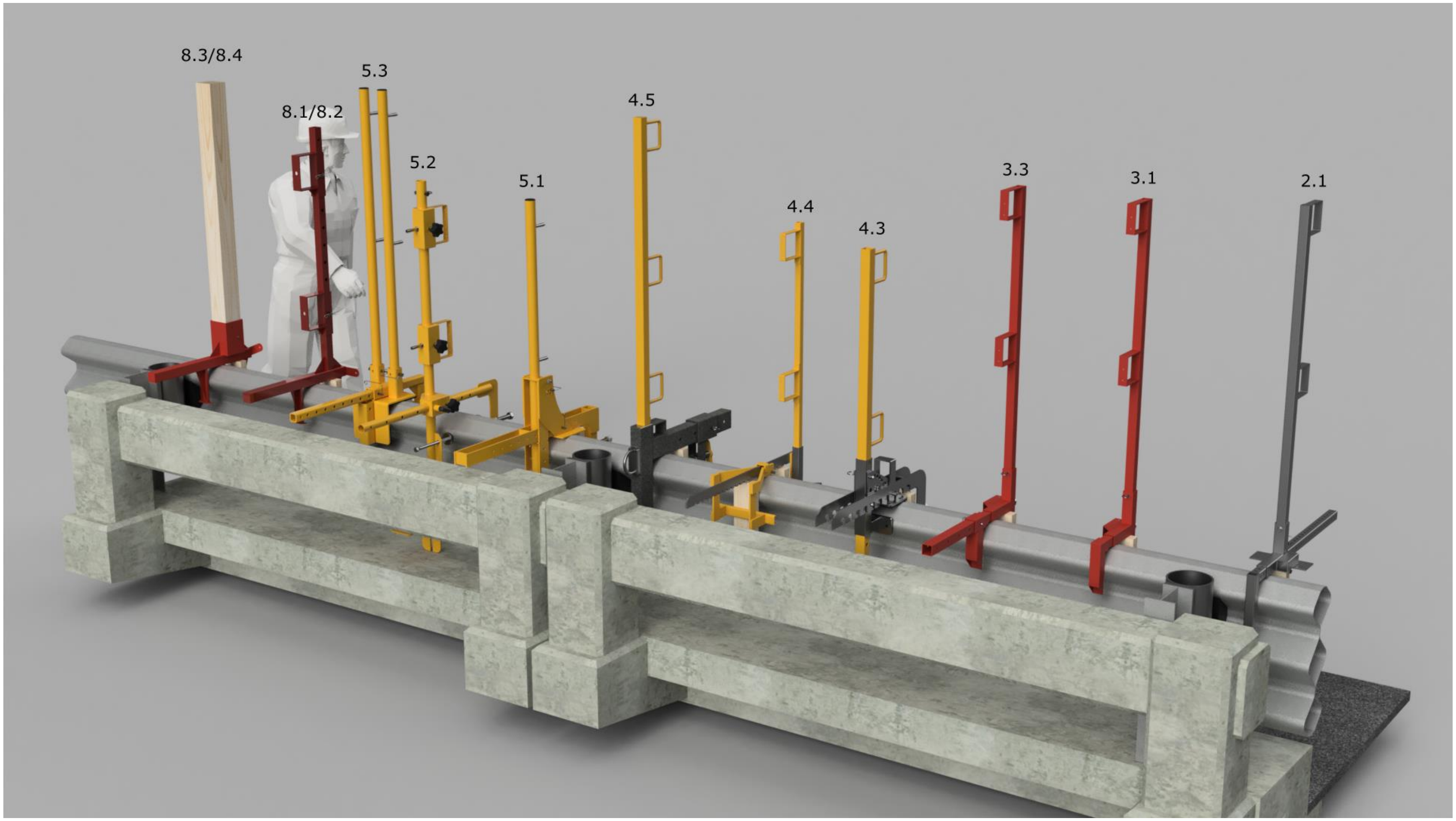


Figure 126 – Guardrail Type 33; view from the southwest

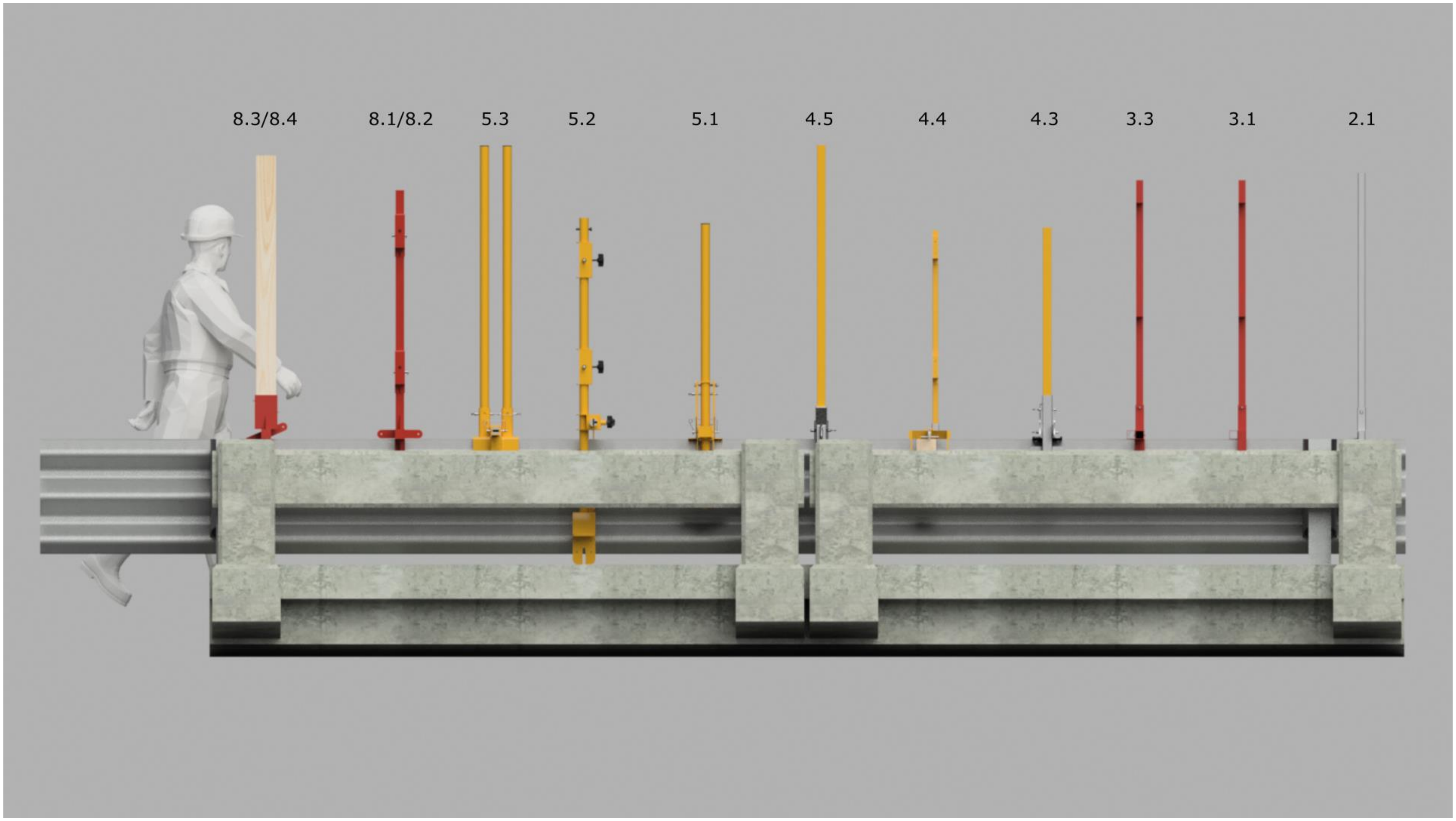


Figure 127 – Guardrail Type 33; view from the west

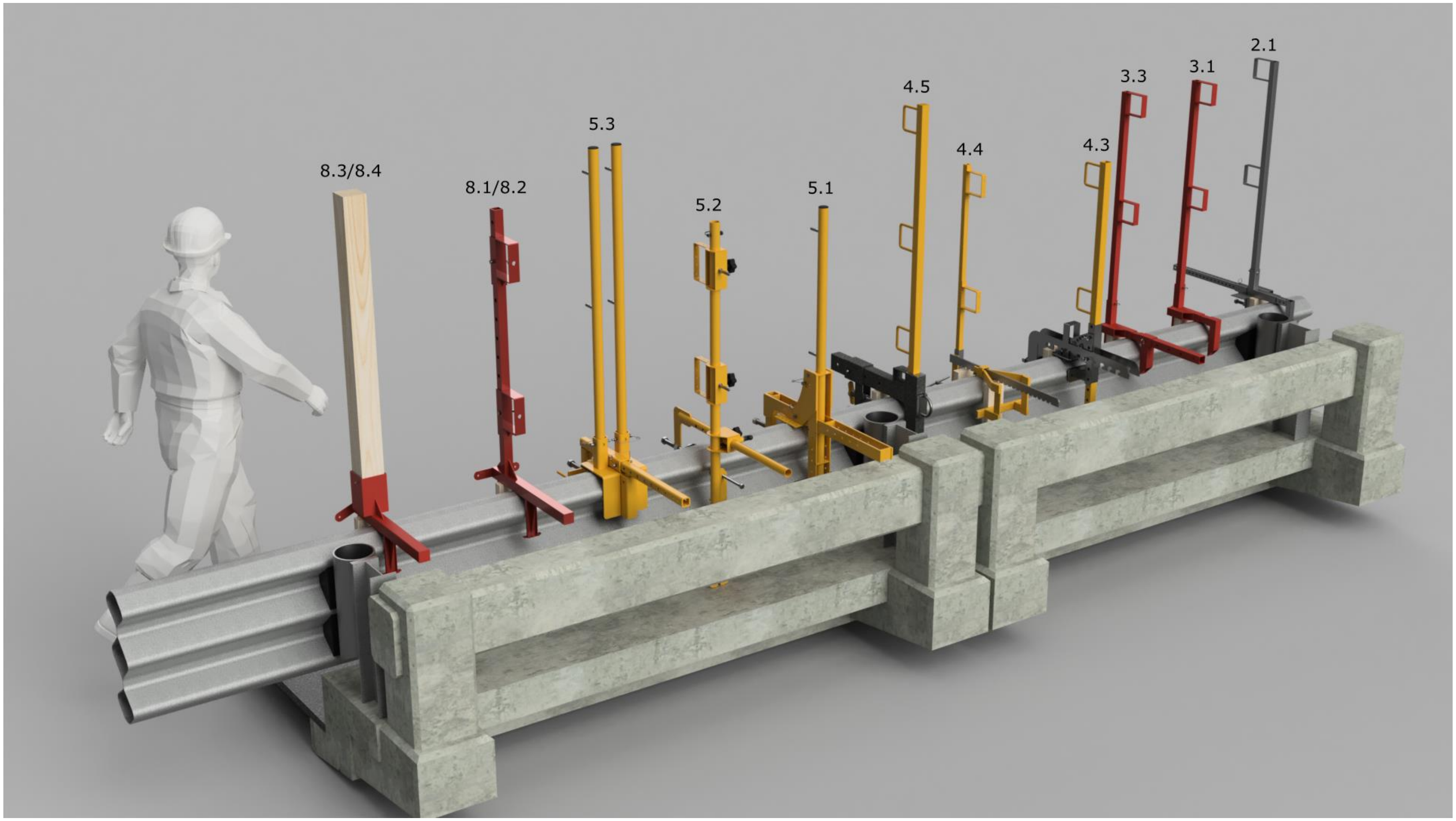


Figure 128 – Guardrail Type 33; view from the northwest

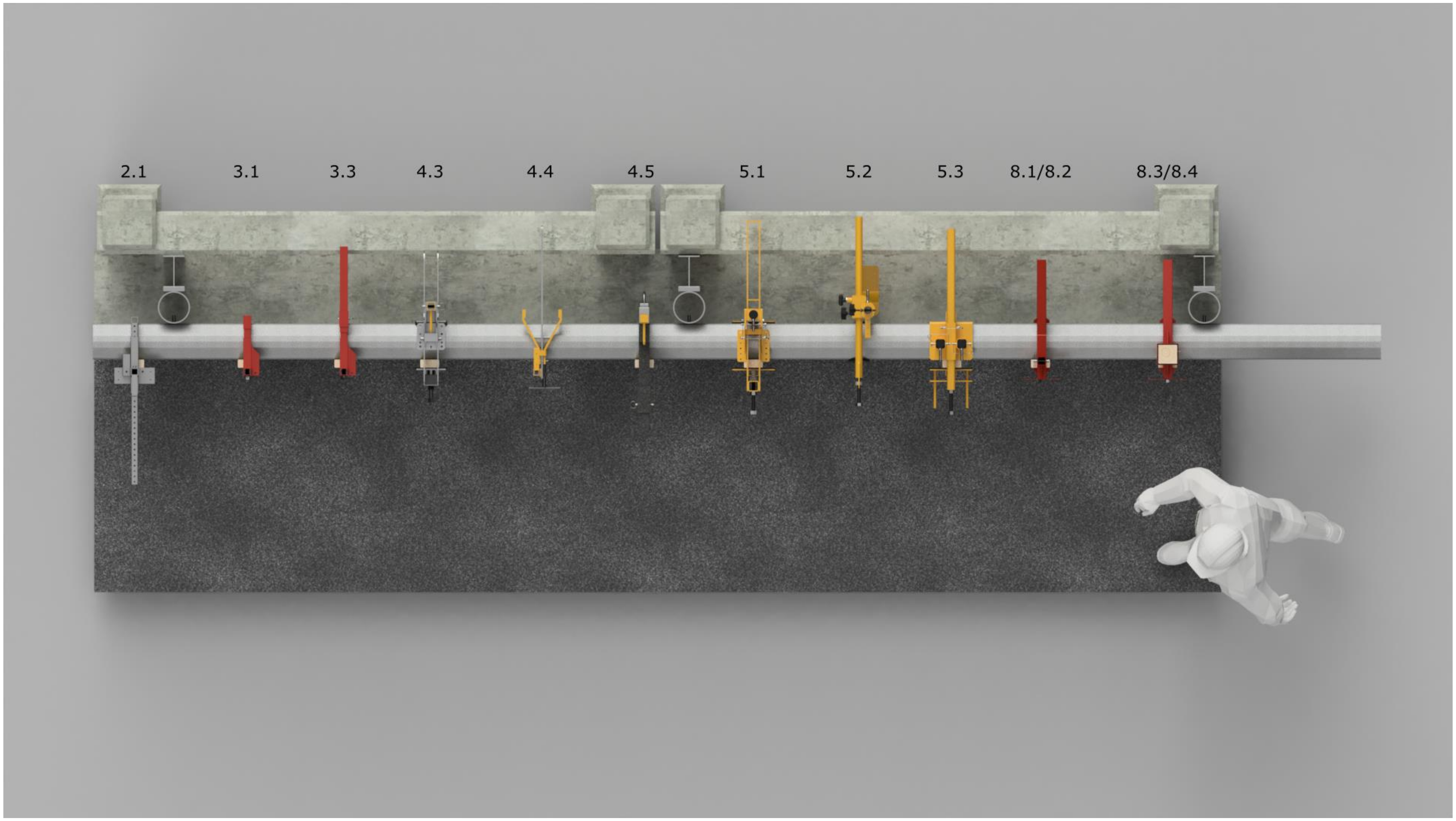


Figure 129 – Guardrail Type 33; view from the top

Appendix D – Field Guide Booklet

Compatibility Testing of Supplemental Fall Protection Devices on NCDOT Bridges

Field Guide Booklet

Research Institution
North Carolina State University

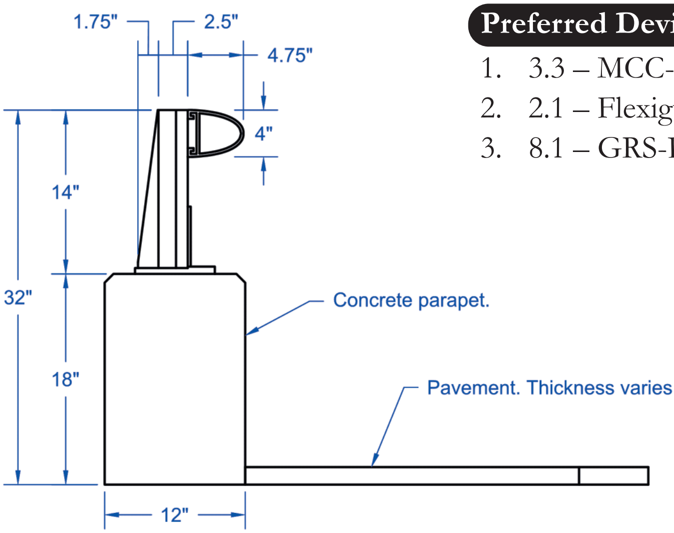
Prepared for
North Carolina Department of Transportation

Table of Contents

Guardrails

Type 01 – Aluminun 1-Bar

18” high, 12” wide concrete parapet with 4.75” x 4” semi-elliptical 1-bar aluminum rail 12” over the concrete parapet. The aluminum bar is supported by steel posts. The guardrail height above working surface is approximately 32”.

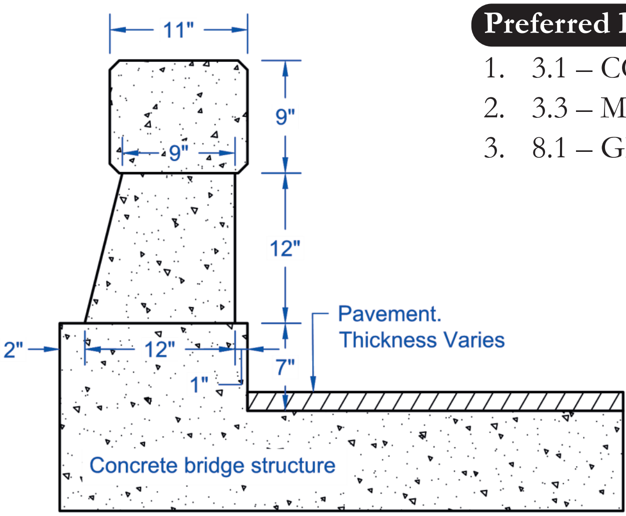


Preferred Devices

1. 3.3 – MCC-130
2. 2.1 – Flexiguard
3. 8.1 – GRS-P12

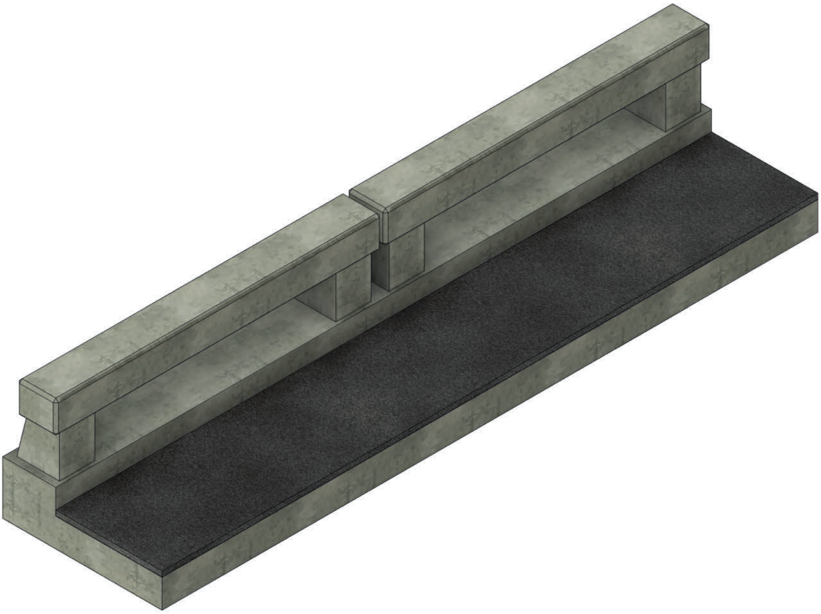
Type 02 – 1-Bar Concrete Rail (Top)

Concrete guardrail section comprised of one reinforced concrete railing bar atop two reinforced concrete supports, one at each end. The guardrail height above working surface is approximately 28".



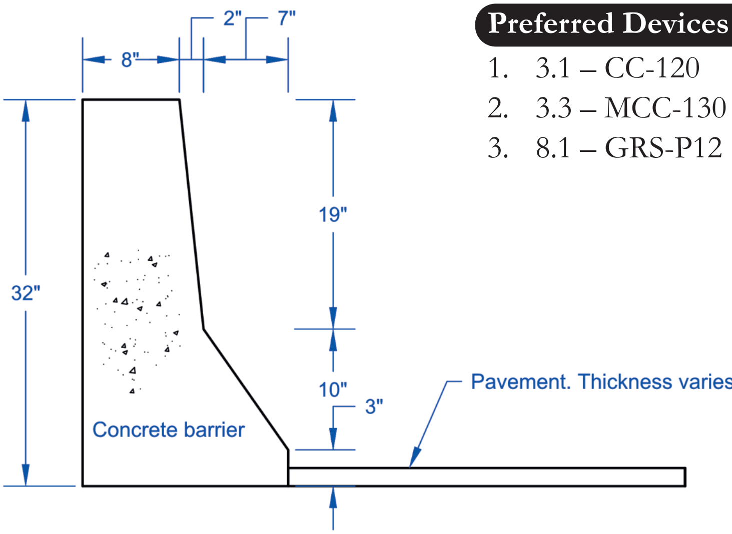
Preferred Devices

1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12



Type 04 – Jersey Barrier

Commonly referred to as "Jersey Barrier", this guardrail comprised of a single reinforced concrete section with flat rear and sloping surfaces in the front. The guardrail height above working surface is approximately 32".

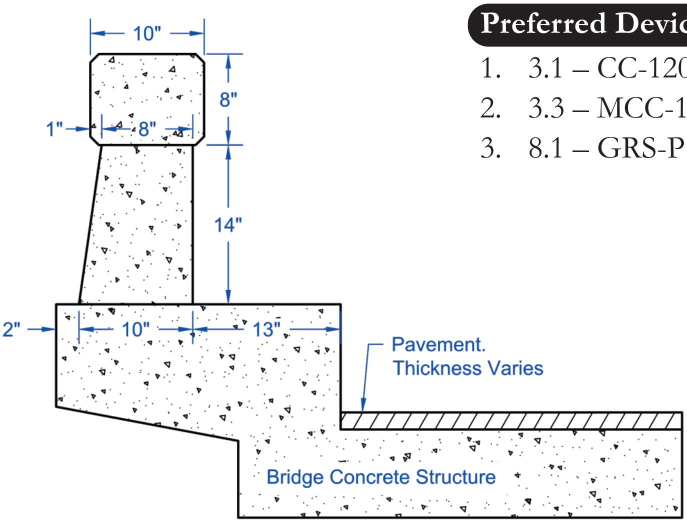


Preferred Devices

1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12

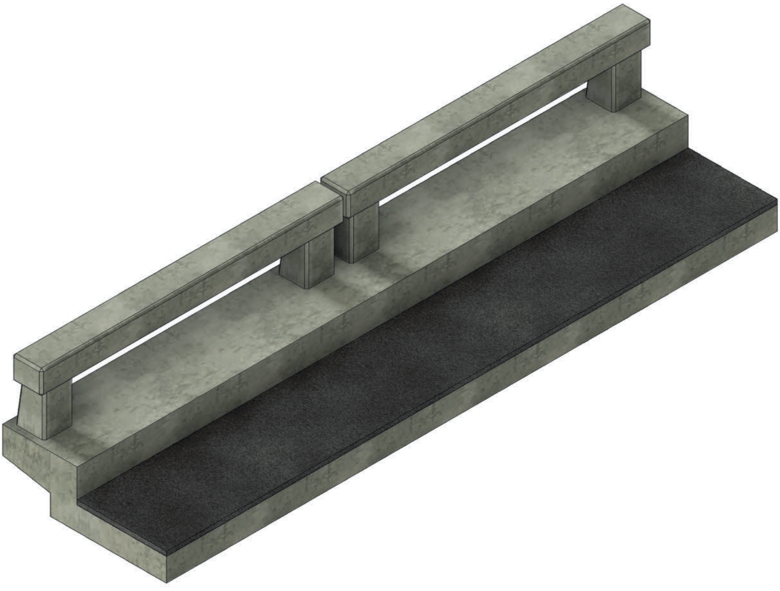
Type 07 – 1-Bar Concrete Rail (Top)

Concrete guardrail section comprised of one reinforced concrete railing bar atop two reinforced concrete supports, one at each end. The guardrail height above working surface is approximately 28".



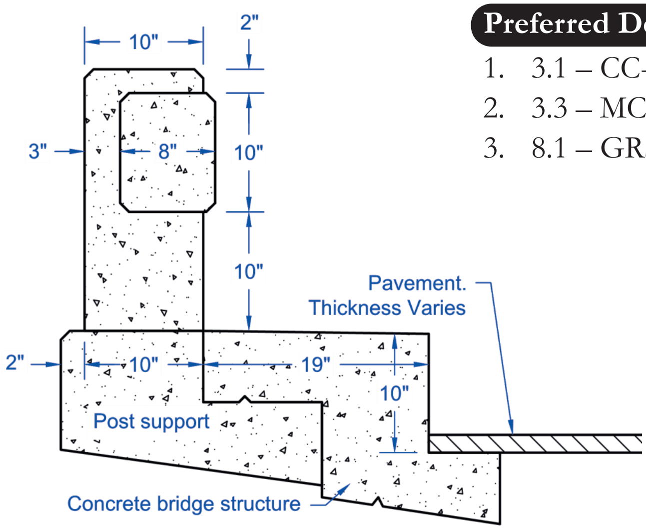
Preferred Devices

1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12



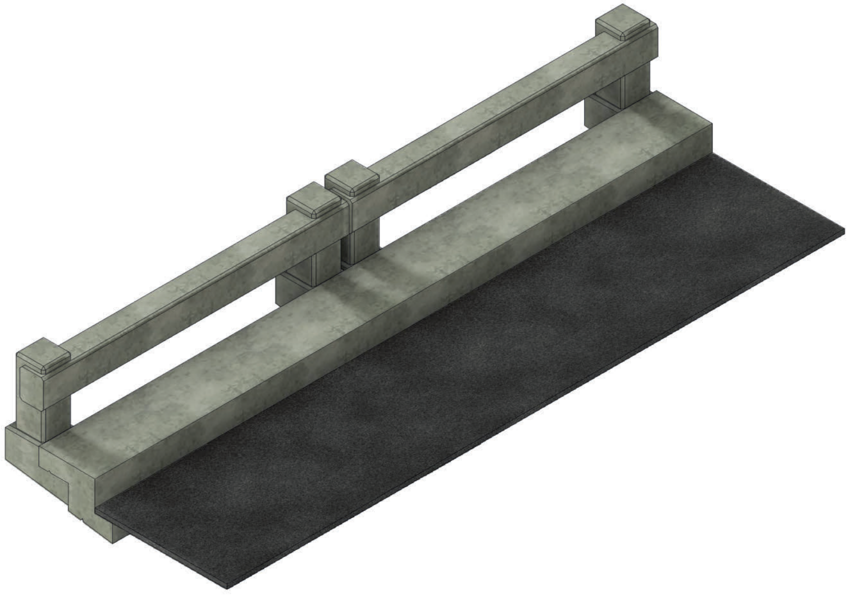
Type 11 – 1-Bar Concrete Rail (Middle)

Concrete guardrail sections comprised of one reinforced concrete railing embedded at mid-height into two reinforced concrete supports, one at each end. The guardrail height above working surface is approximately 22".



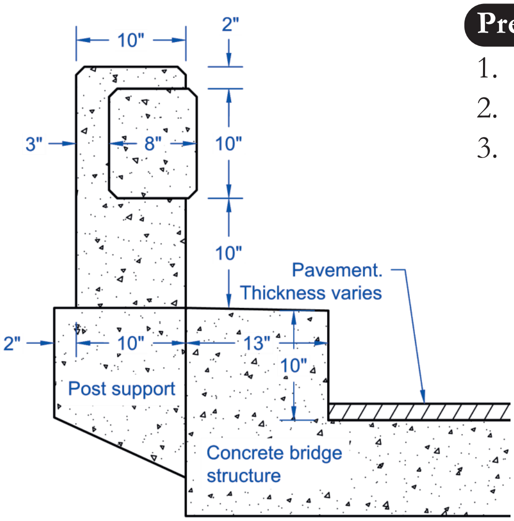
Preferred Devices

1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12



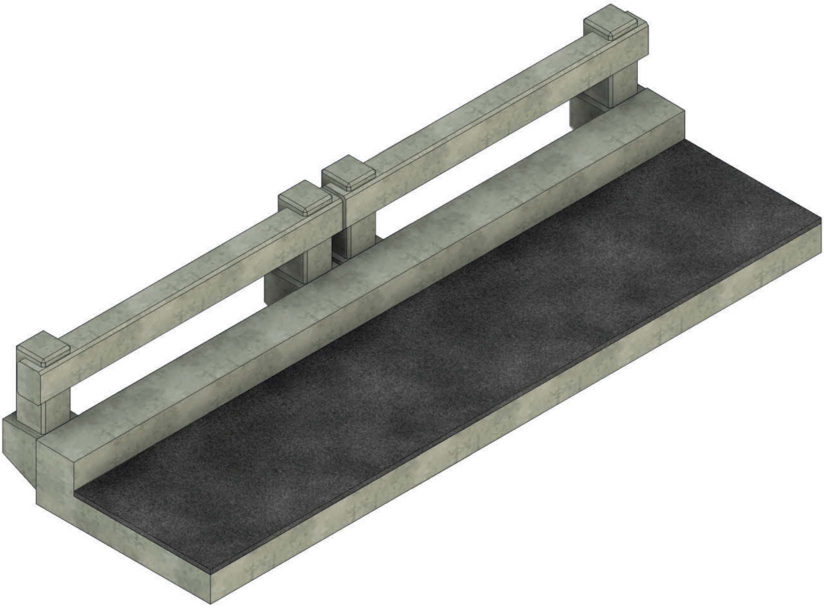
Type 14 & 24 – 1-Bar Concrete Rail (Middle)

Concrete guardrail sections comprised of one reinforced concrete railing embedded at mid-height into two reinforced concrete supports, one at each end. The concrete post and mid-height rail are equal to Type 11. However, the width of the curb adjacent to the guardrails varies. The guardrail height above working surface is approximately 22”.



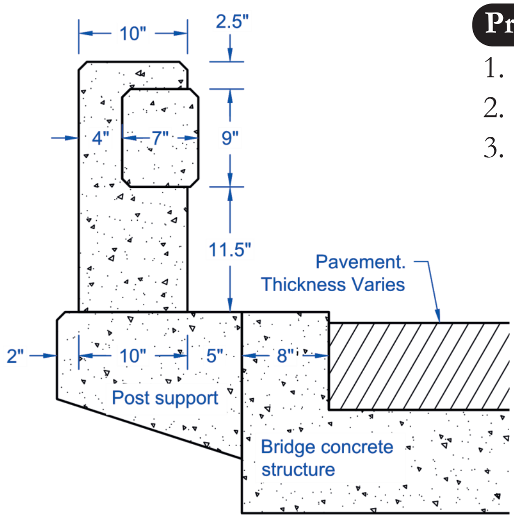
Preferred Devices

1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12



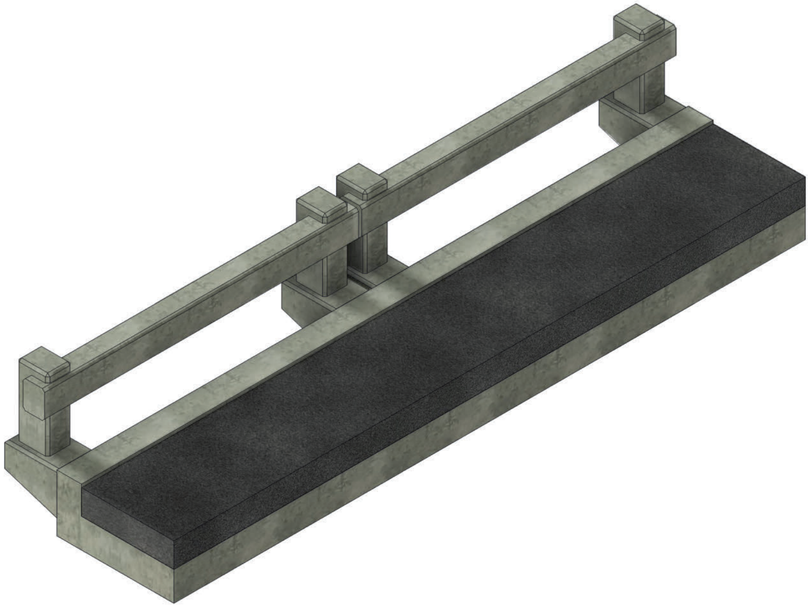
Type 14 Variation 2

In comparison with variation 1, variation 2 dimension vary in the concrete bar (width and height are smaller by 1”), height of the post (1” higher), and dimensions of the post support. There is a noticeable gap between the bridge structure and the guardrail, increasing the fall risk for the workers and increasing the difficulty of FPSD installation. The guardrail height above working surface is approximately 23”.



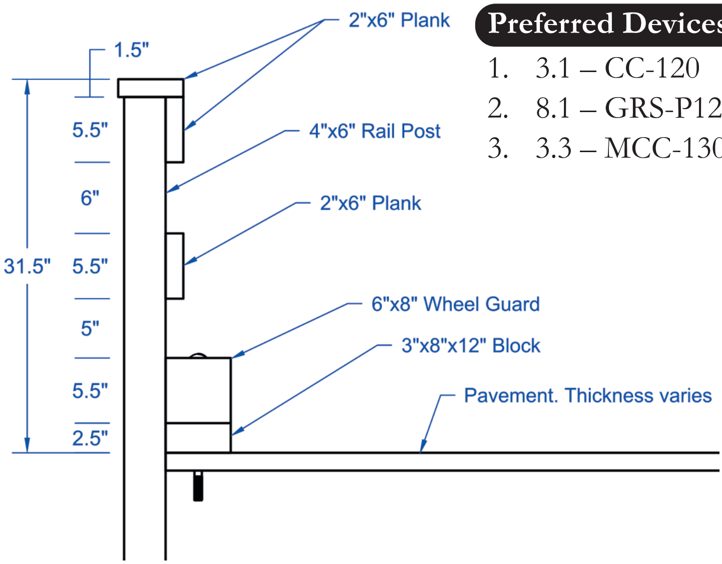
Preferred Devices

1. 3.1 – CC-120
2. 8.1 – GRS-P12
3. 2.1 – Flexiguard



Type 22 – Wood Guardrail

Guardrail type constructed mainly of dimensional lumber. It is comprised of a wheel guard close to the working surface, 4"x6" posts supporting one 2"x6" mid rail, and a two perpendicular 2"x6" planks as top rail. The guardrail height above working surface is approximately 32".

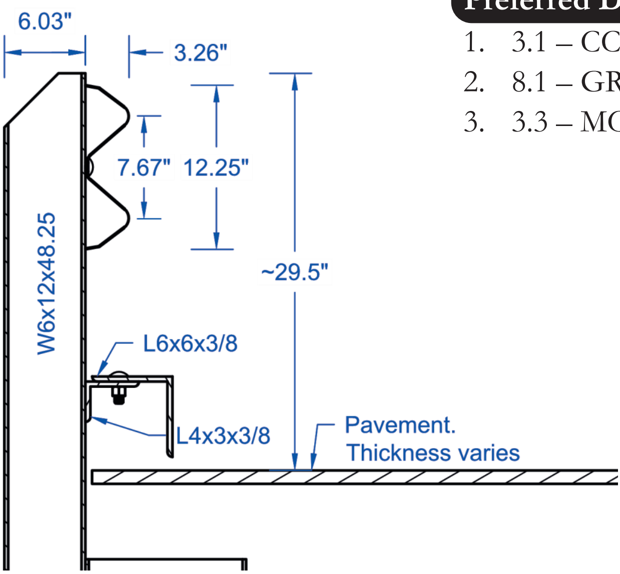


Preferred Devices

1. 3.1 – CC-120
2. 8.1 – GRS-P12
3. 3.3 – MCC-130

Type 23 – W-Beam

Commonly referred to as "W-beam" bridge rail, the guardrail is comprised of a W-shape steel section bolted to structural steel grade posts. This guardrail shape is also used in longitudinal barriers along highways and transitions from longitudinal barriers to bridge guardrails. The guardrail height above working surface is approximately 30".

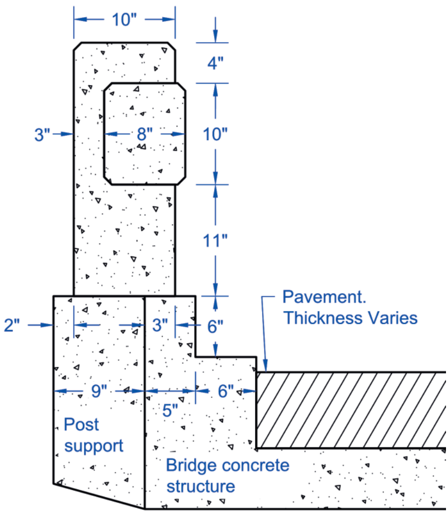


Preferred Devices

1. 3.1 – CC-120
2. 8.1 – GRS-P12
3. 3.3 – MCC-130

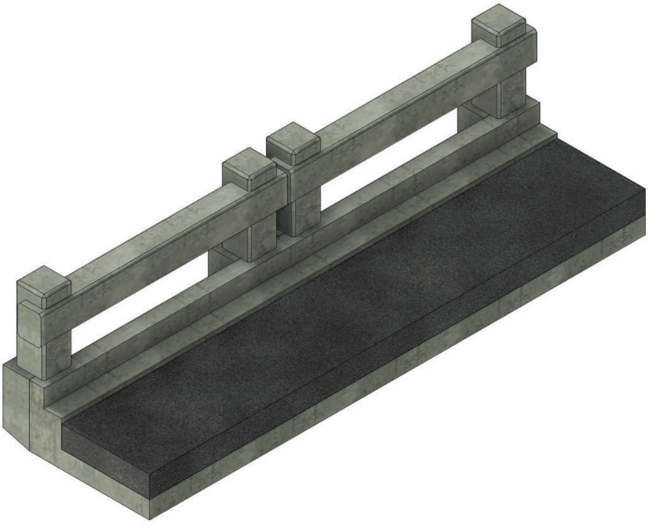
Type 24 Variation 2

Concrete guardrail sections comprised of one reinforced concrete railing embedded at mid-height into two reinforced concrete supports, one at each end. The concrete post and mid-height rail are equal to Variation 1. However, the curb and post structure varies. The guardrail height above working surface is approximately 31”.



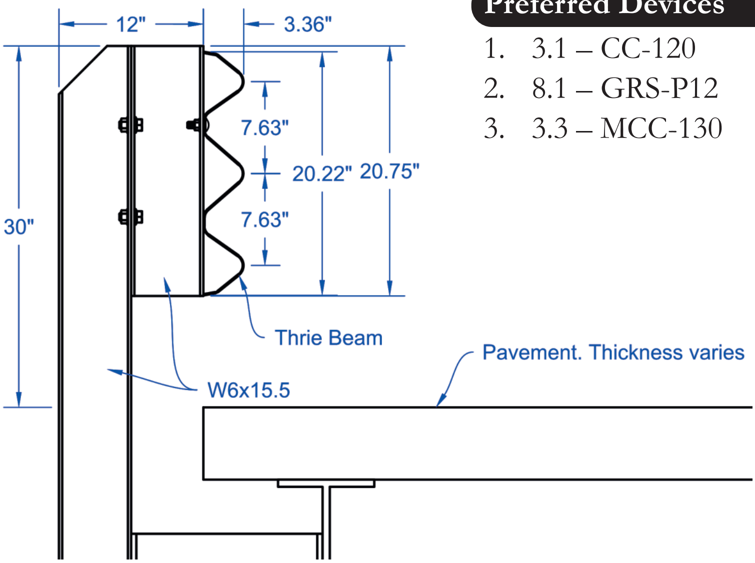
Preferred Devices

1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12



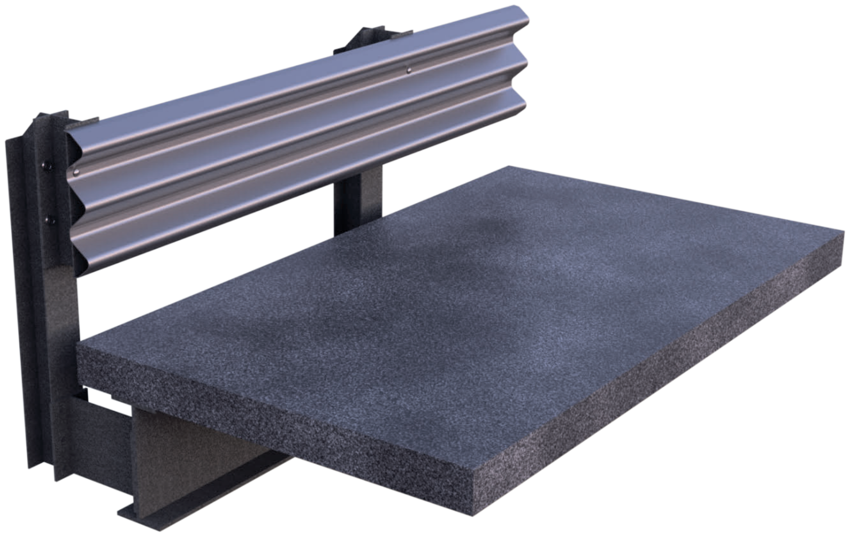
Type 25 – Thrie-Beam

Commonly referred to as "Thrie-beam" bridge rail, the guardrail is comprised of a special shape steel section bolted to structural steel grade posts. This guardrail shape is also popular in bridge guardrail retrofits. The guardrail height above working surface is approximately 30".



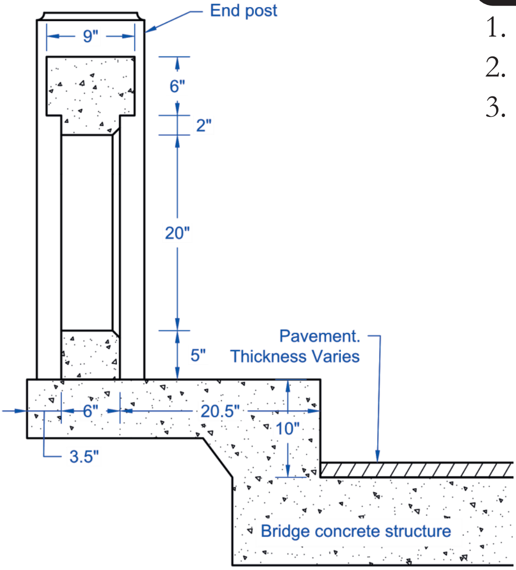
Preferred Devices

1. 3.1 – CC-120
2. 8.1 – GRS-P12
3. 3.3 – MCC-130



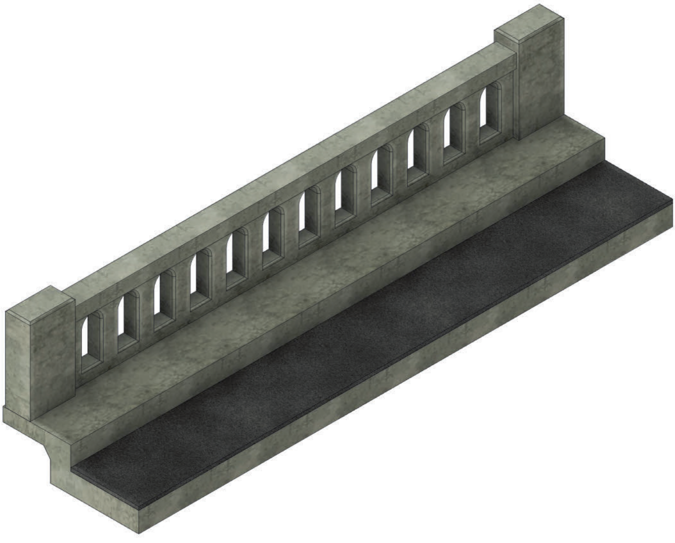
Type 31 – Concrete Church Window

Commonly referred to as "Church Window", this guardrail comprised of vertical reinforced concrete sections with elliptical openings equally spaced between reinforced concrete end posts. The guardrail height above the working surface is approximately is 33".



Preferred Devices

1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12

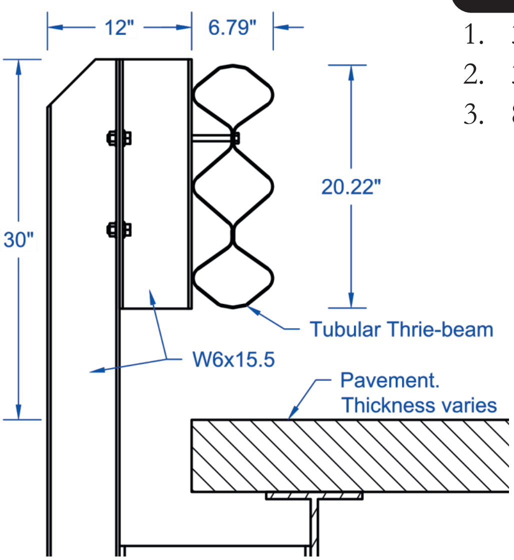


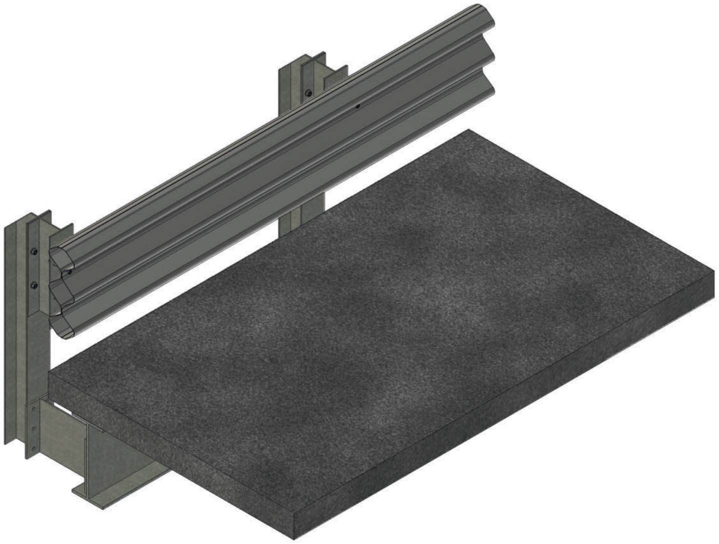
Type 32 – Tubular Thrie-Beam

Guardrail comprised of a horizontal steel section commonly known as "Tubular Thrie-beam", bolted to structural steel grade posts. Similar to Guardrail Type 25, there may be a curb below the guardrail. The guardrail height above the working surface is approximately is 30".

Preferred Devices

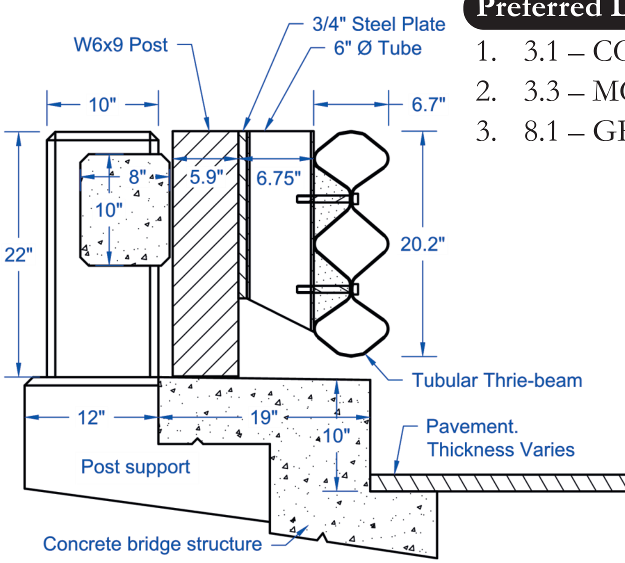
1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12





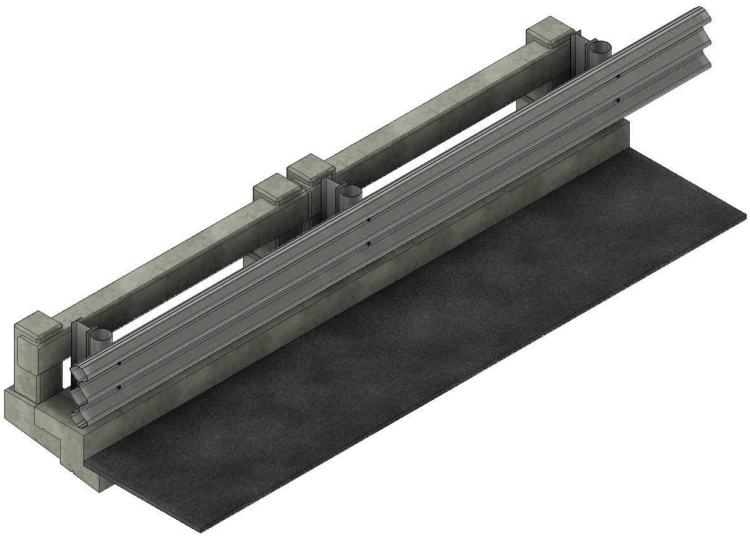
Type 33 – Tubular Thrie-Beam Retrofit

This guardrail type is a typical retrofit to concrete 1-bar guardrails (e.g. Type 11) using a tubular thrie-beam sections placed in front of the existing guardrail. The installation of the FPSD is possible in either the concrete bar or the tubular thrie-beam. The apporximate guardrail height above working surface is 32".



Preferred Devices

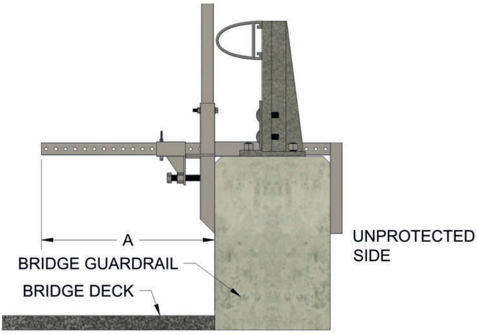
1. 3.1 – CC-120
2. 3.3 – MCC-130
3. 8.1 – GRS-P12

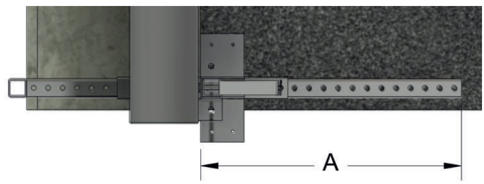


Fall Protection Supplementary Devices

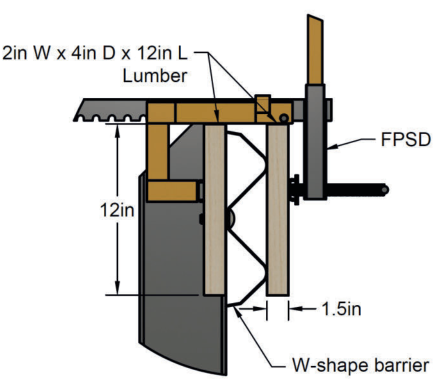
Notes

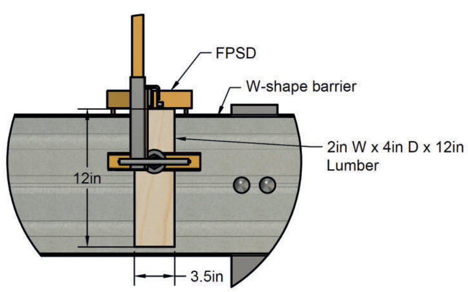
1. The protrusion for each FPSD was measured at the protected side, from the point of contact between the FPSD and the guardrail. See dimension "A" in the figures below.





2. Due to the irregular shape of some guardrails, or to the clamping limitations for some FPSD, additional items may be needed to ensure proper fit. Because in most cases, the guardrail width is lesser than the minimum clamping distance of the FPSD, the minimum width (W) and length (L) of the wood blocks are reported. Depth (D) is not a concern and will not be reported. If wider or longer wood blocks are available, these can be used unless otherwise noted. For example, 2"W, 4"D, and 12"L (nominal dimensions) are shown in the figures below. In this case, 4"W, 6"D, 16"L will work as well. However, no smaller blocks than specified can be used. The dimensions shown in the drawings are actual dimensions.





ID No.: 2.1
Manufacturer: DBI Sala
Product Name: Flexiguard Portable Guardrail

Characteristics

Weight: 18 lbs.
Railings: Additional item. 2"x4" lumber.
Clamp Range: 6" to 24".
Usage: Slab clamp; Parapet clamp.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 18".

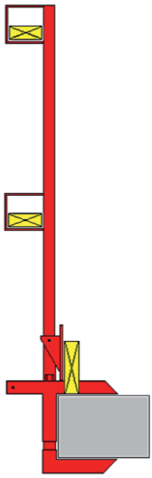
Type 04: Fits on parapet. Protrusion is 22.5".

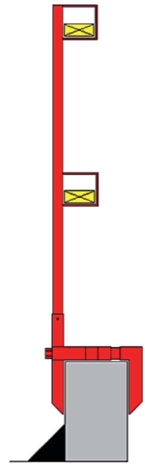
Type 22: Fits on guardrail with placement of 6"W x 6"L lumber at the back of the guardrail. Protrusion is 23". No wheel guard fit.

Type 23: Fits on guardrail with placement of 4"W x 8"L lumber at the front of the guardrail. Protrusion is 27.25". The device also fits on wheel guard. Intrusion into work area is 24".

Type 25: Fits on guardrail with placement of 4"W x 8"L lumber at the front of the guardrail. Protrusion is 26.75".

ID No.: 3.1
Manufacturer: Fall Protection Guardrail Systems
Product Name: C-Clamp CC120





Characteristics

Weight: 13 lbs.
Railings: Additional item. 2"x4" lumber.
Clamp Range: 7" to 12".
Usage: Slab clamp; Parapet clamp.

Compatibility Testing Results

Type 01: No parapet fit. The devices fits on the aluminum rail with placement of 2"W x 12"L lumber at the back of the guardrail, and 2"W x 18"L at the front. Protrusion is 3.75".

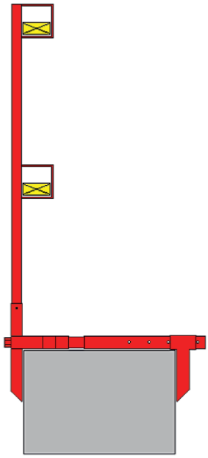
Type 04: Fits on parapet. Protrusion is 3".

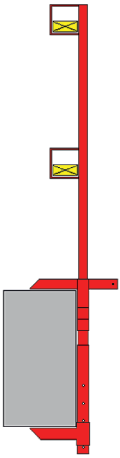
Type 22: Fits on guardrail with placement of 6"W x 6"L lumber at the back of the guardrail. Protrusion is 2.25". No wheel guard fit.

Type 23: Fits on guardrail with placement of 6"W x 8"L lumber at the front of the guardrail. Protrusion is 7.75". The device also fits on wheel guard with placement of 2"W x 6"L (maximum lenght). Protrusion is 3.75".

Type 25: Fits on guardrail with placement of 6"W x 8"L lumber at the back of the guardrail. Protrusion is 7.75".

ID No.:	3.3
Manufacturer:	Fall Protection Guardrail Systems
Product Name:	Master Clamp MCC130





Characteristics

Weight: 15 lbs.
Railings: Additional item. 2"x4" lumber.
Clamp Range: 8" to 48".
Usage: Slab clamp; Parapet clamp.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 2.25".

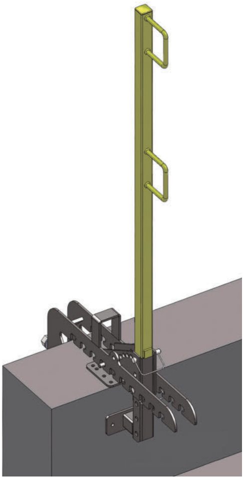
Type 04: Fits on parapet. Protrusion is 3".

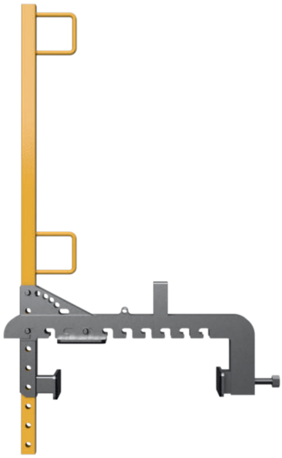
Type 22: Fits on guardrail with placement of 8"W x 6"L lumber at the back of the guardrail. Protrusion is 2.25". No wheel guard fit.

Type 23: Fits on guardrail with placement of 6"W x 8"L lumber at the front of the guardrail. Protrusion is 7.75". The device also fits on wheel guard with placement of 4"W x 6"L (maximum lenght). Protrusion is 5.75".

Type 25: Fits on guardrail with placement of 6"W x 8"L lumber at the back of the guardrail. Protrusion is 7.75".

ID No.: 4.3
Manufacturer: Guardian Fall Protection
Product Name: Alligator Parapet Guardrail System





Characteristics

Weight: 42 lbs.
Railings: Additional item. 2"x4" lumber.
Clamp Range: 2" to 16".
Usage: Parapet clamp.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 6.5".

Type 04: Fits on parapet. Protrusion is 7".

Type 22: Fits on guardrail with placement of 4"W x 6"L lumber at the back of the guardrail. Protrusion is 6.5". No wheel guard fit.

Type 23: Fits on guardrail with placement of 2"W x 8"L lumber at the front and back of the guardrail. Protrusion is 8". No wheel guard fit.

Type 25: Fits on guardrail with placement of 2"W x 8"L lumber at the front and back of the guardrail. Protrusion is 8".

ID No.: 4.4
Manufacturer: Guardian Fall Protection
Product Name: Parapet Clamp Guardrail System

Characteristics

Weight: 38 lbs.
Railings: Additional item. 2"x4" lumber.
Clamp Range: 4" to 16".
Usage: Parapet clamp.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 7".

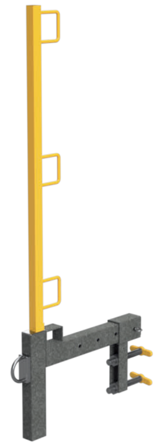
Type 04: Fits on parapet. Protrusion is 7.25".

Type 22: Fits on guardrail with placement of 4"W x 6"L lumber at the back of the guardrail. Protrusion is 6.75". The device also fits on wheel guard.

Type 23: Fits on guardrail with placement of 2"W x 8"L lumber at the front and back of the guardrail. Protrusion is 8.25". The device also fits on wheel guard.

Type 25: Fits on guardrail with placement of 2"W x 8"L lumber at the front and back of the guardrail. Protrusion is 8.25".

ID No.: 4.5
Manufacturer: Guardian Fall Protection
Product Name: Parapet Anchor



Characteristics

Weight: 33 lbs.
Railings: Additional item. 2"x4" lumber.
Clamp Range: 4" to 20".
Usage: Parapet clamp; Anchor for personal fall arrest & restraint systems.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 9".

Type 04: Fits on parapet. Protrusion is 13".

Type 22: Fits on guardrail with placement of 6"W x 6"L lumber at the back of the guardrail. Protrusion is 18.25". No wheel guard fit.

Type 23: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 17.75". No wheel guard fit.

Type 25: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 17.75".

ID No.: 5.1
Manufacturer: AES Raptor
Product Name: RaptorRail

Characteristics

Weight: 37 lbs.
Railings: Proprietary, metallic. Rails sold in various lenghts.
Clamp Range: 3" to 24".
Usage: Parapet clamp.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 8.75".

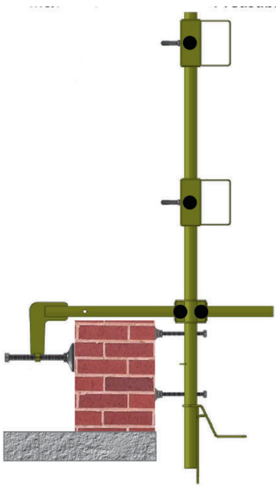
Type 04: Fits on parapet. Protrusion is 9.5".

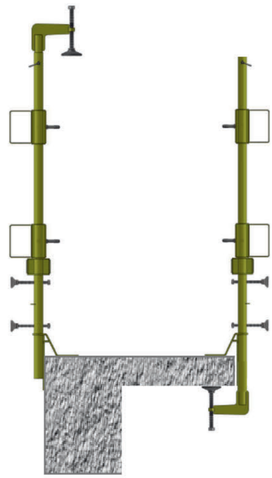
Type 22: Fits on guardrail with placement of 4"W x 6"L lumber at the back of the guardrail. Protrusion is 8.75". No wheel guard fit.

Type 23: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 10.25". No wheel guard fit.

Type 25: Fits on guardrail. Protrusion is 8.75".

ID No.: 5.2
Manufacturer: AES Raptor
Product Name: All-in-One





Characteristics

Weight: 25 lbs.
Railings: Proprietary metallic or 2"x4" lumber.
Clamp Range: 0" to 24".
Usage: Slab clamp; Parapet clamp.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 8.75".

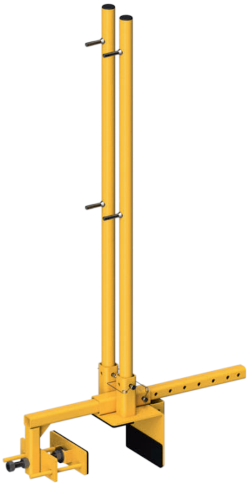
Type 04: Fits on parapet. Protrusion is 9.25".

Type 22: Fits on guardrail with placement of 2"W x 12"L lumber at the back of the guardrail. Protrusion is 8.75". No wheel guard fit.

Type 23: Fits on guardrail. Protrusion is 8.75". No wheel guard fit.

Type 25: Fits on guardrail. Protrusion is 8.75".

ID No.: 5.3
Manufacturer: AES Raptor
Product Name: Universal Guardrail Parapet Clamp



Characteristics

Weight: 37 lbs.
Railings: Proprietary, metallic. Rails sold in various lenghts.
Clamp Range: 4.5" to 24".
Usage: Slab clamp; Parapet clamp.

Compatibility Testing Results

Type 01: Fits on parapet. Protrusion is 8.75"

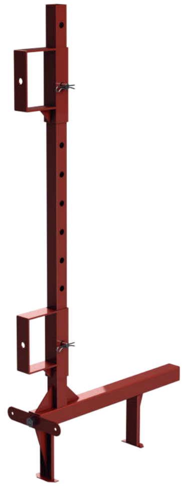
Type 04: Fits on parapet. Protrusion is 9.25".

Type 22: Fits on guardrail with placement of 6"W x 6"L lumber at the back of the guardrail. Protrusion is 8.75". The devices also fits on wheel guard.

Type 23: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 12.25". The device also fits on wheel guard.

Type 25: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 10.25"

ID No.: 8.1 /8.2
Manufacturer: Ellis Manufacturing
Product Name: Parapet Guard. GRS-P12 / GRS-P24



Characteristics

Weight: 25 lbs.
Railings: Additional Item. 2"x4" lumber.
Clamp Range: 4" to 12" / 4" to 24".
Usage: Parapet clamp.

Compatibility Testing Results

Type 01: No parapet fit. Fits on aluminum rail with placement of 2"W x 18"L at the front of the guardrail. Protrusion is 4.25"

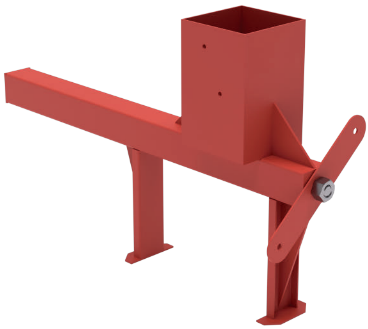
Type 04: Fits on parapet. Protrusion is 3.5".

Type 22: Fits on guardrail with placement of 6"W x 6"L lumber at the back of the guardrail. Protrusion is 2.75". The device also fits on wheel guard.

Type 23: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 4.5". The device also fits on wheel guard.

Type 25: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 4.25".

ID No.: 8.3
Manufacturer: Ellis Manufacturing
Product Name: QuickRail Parapet Guardrail QR-P12



Characteristics

Weight: 19 lbs. including 4"x4"x48" lumber post.
Railings: Additional Item. 2"x4" lumber fastened to lumber post
Clamp Range: 4" to 12"
Usage: Parapet clamp.

Compatibility Testing Results

Type 01: No parapet fit. Fits on aluminum rail with placement of 2"W x 18"L at the front of the guardrail. Protrusion is 4.5"

Type 04: Fits on parapet. Protrusion is 3.5".

Type 22: Fits on guardrail with placement of 6"W x 6"L lumber at the back of the guardrail. Protrusion is 2.75". No wheel guard fit.

Type 23: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 4.5". No wheel guard fit.

Type 25: Fits on guardrail with placement of 2"W x 8"L lumber at the front of the guardrail. Protrusion is 4.25".

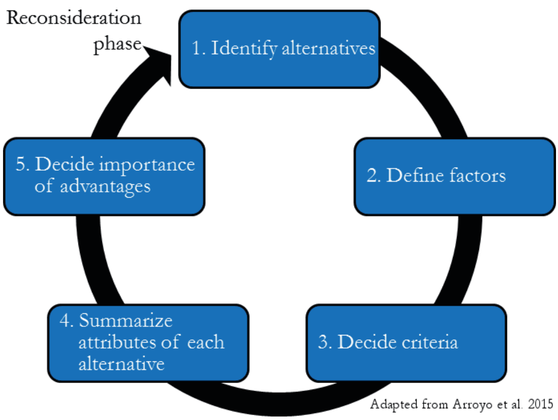
Choosing by Advantages

Choosing by Advantages (CBA) is a process to make sound decisions based on the importance of the advantages between alternatives, which are anchored on relevant facts (Suhr 1999). It's implementation began in 1969 at the U.S. Forest Service.

Important Definitions

Factor: element, part, or component of a decision.
Criteria: rule or guideline to make a decision. Criteria can be *must* or *want*.
Attribute: characteristic, quality, or consequence of one alternative.
Advantage: a difference between the attributes of **two** alternatives.

Steps of Choosing by Advantages



Adapted from Arroyo et al. 2015

1. Identify the alternatives.
2. Define factors that differentiate the alternatives and that are important for making the decision.
3. Decide the *must* and *want* criteria for each of the factors.
4. Summarize the attributes of each alternative.
5a. Underline or highlight the least-preferred attribute in each factor. If there are two of the same, mark only one.
5b. Summarize the differences for each factor against the least preferred attribute. When there is no advantage, the space is left blank.
5c. Circle the most important advantage in each factor. If there are two of the same, mark only one.
5d. Select the paramount advantage and establish a convenient scale of importance (e.g., 1 – 10, 1 – 100).
5e. Weigh the remaining advantages compared directly or indirectly to the paramount advantage using the same scale of importance.

Appendix E – Choosing by Advantages (CBA) Summary Tables

Type 01

	Alternative 1 2.1 Flexiguard	Alternative 2 3.1 C-Clamp CC120	Alternative 3 3.3 MCC-130	Alternative 4 4.3 Alligator	Alternative 5 4.4 Parapet Clamp	Alternative 6 4.5 Parapet Anchor	Alternative 7 5.1 RaptorRail	Alternative 8 5.2 All-in-One	Alternative 9 5.3 UGPC	Alternative 10 8.1 - GRS-P12	Alternative 11 8.3 QR-P12
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	3	8	2	7	7	2	4	9	5	8	10
Advantage:	7	2	8	3	3	8	6	1	5	2	0
Importance of Advantage	87.14	22.86	100.00	35.71	35.71	100.00	74.29	10.00	61.43	22.86	0.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	18	3.75	2.25	6.5	7	9	8.75	8.75	8.75	4.5	4.5
Advantage:	9.25	23.5	25	20.75	20.25	18.25	18.5	18.5	18.5	22.75	22.75
Importance of Advantage	36.95	84.95	90.00	75.68	74.00	67.26	68.11	68.11	68.11	82.42	82.42
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	2	8	2	8	2	7	7	9	4	2	5
Advantage:	8	2	8	2	8	3	3	1	6	8	5
Importance of Advantage	75.63	19.38	75.63	19.38	75.63	28.75	28.75	10.00	56.88	75.63	47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	4	5	5	6	4	4	5	4	5	4	7
Advantage:	4	3	3	2	4	4	3	4	3	4	1
Importance of Advantage	50.00	40.00	40.00	30.00	50.00	50.00	40.00	50.00	40.00	50.00	20.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18	13	15	42	38	33	37	25	37	23	19
Advantage:	24	29	27	0	4	9	5	17	5	19	23
Importance of Advantage	66.00	80.00	74.40	0.00	10.00	24.00	12.80	46.40	12.80	52.00	63.20
Aggregate importance of advantages	316	247	380	161	245	270	224	185	239	283	213

Type 02

	Alternative 1 2.1 Flexiguard	Alternative 2 3.1 C-Clamp CC120	Alternative 3 3.3 MCC-130	Alternative 4 4.3 Alligator	Alternative 5 4.4 Parapet Clamp	Alternative 6 4.5 Parapet Anchor	Alternative 7 5.1 RaptorRail	Alternative 8 5.2 All-in-One	Alternative 9 5.3 UGPC	Alternative 10 8.1 - GRS-P12	Alternative 11 8.3 QR-P12
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	3	2	2	5	5	3	4	8	4	3	9
Advantage:	7	8	8	5	5	7	6	2	6	7	1
Importance of Advantage	87.14	100.00	100.00	61.43	61.43	87.14	74.29	22.86	74.29	87.14	10.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	5.5	2.25	2.25	6.75	6.75	10	8.75	8.75	8.75	2.75	2.75
Advantage:	21.75	25	25	20.5	20.5	17.25	18.5	18.5	18.5	24.5	24.5
Importance of Advantage	79.05	90.00	90.00	74.84	74.84	63.89	68.11	68.11	68.11	88.32	88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	2	2	2	7	2	7	7	9	4	2	5
Advantage:	8	8	8	3	8	3	3	1	6	8	5
Importance of Advantage	75.63	75.63	75.63	28.75	75.63	28.75	28.75	10.00	56.88	75.63	47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	4	3	5	6	4	4	5	4	5	3	6
Advantage:	4	5	3	2	4	4	3	4	3	5	2
Importance of Advantage	50.00	60.00	40.00	30.00	50.00	50.00	40.00	50.00	40.00	60.00	30.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18	13	15	42	38	33	37	25	37	23	19
Advantage:	24	29	27	0	4	9	5	17	5	19	23
Importance of Advantage	66.00	80.00	74.40	0.00	10.00	24.00	12.80	46.40	12.80	52.00	63.20
Aggregate importance of advantages	358	406	380	195	272	254	224	197	252	363	239

Type 04

	Alternative 1		Alternative 2		Alternative 3		Alternative 4		Alternative 5		Alternative 6		Alternative 7		Alternative 8		Alternative 9		Alternative 10		Alternative 11	
	2.1 Flexiguard		3.1 C-Clamp CC120		3.3 MCC-130		4.3 Alligator		4.4 Parapet Clamp		4.5 Parapet Anchor		5.1 RaptorRail		5.2 All-in-One		5.3 UGPC		8.1 - GRS-P12		8.3 QR-P12	
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	2		2		2		5		5		3		4		8		4		3		9	
Advantage:	8		8		8		5		5		7		6		2		6		7		1	
Importance of Advantage		100.00		100.00		100.00		61.43		61.43		87.14		74.29		22.86		74.29		87.14		10.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	22.5		3		3		8		7.25		13		9.5		9.25		9.25		3.5		3.5	
Advantage:	4.75		24.25		24.25		19.25		20		14.25		17.75		18		18		23.75		23.75	
Importance of Advantage		21.79		87.47		87.47		70.63		73.16		53.79		65.58		66.42		66.42		85.79		85.79
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	2		2		2		8		2		7		7		9		4		2		5	
Advantage:	8		8		8		2		8		3		3		1		6		8		5	
Importance of Advantage		75.63		75.63		75.63		19.38		75.63		28.75		28.75		10.00		56.88		75.63		47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	4		3		5		6		4		4		5		4		5		3		6	
Advantage:	4		5		3		2		4		4		3		4		3		5		2	
Importance of Advantage		50.00		60.00		40.00		30.00		50.00		50.00		40.00		50.00		40.00		60.00		30.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18		13		15		42		38		33		37		25		37		23		19	
Advantage:	24		29		27		0		4		9		5		17		5		19		23	
Importance of Advantage		66.00		80.00		74.40		0.00		10.00		24.00		12.80		46.40		12.80		52.00		63.20
Aggregate importance of advantages		313		403		377		181		270		244		221		196		250		361		236

Type 07

Factor / Criteria		Alternative 1 2.1 Flexiguard	Alternative 2 3.1 C-Clamp CC120	Alternative 3 3.3 MCC-130	Alternative 4 4.3 Alligator	Alternative 5 4.4 Parapet Clamp	Alternative 6 4.5 Parapet Anchor	Alternative 7 5.1 RaptorRail	Alternative 8 5.2 All-in-One	Alternative 9 5.3 UGPC	Alternative 10 8.1 - GRS-P12	Alternative 11 8.3 QR-P12
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest	**Atribute:**	3	2	2	5	5	3	4	8	4	3	9
	Advantage:	7	8	8	5	5	7	6	2	6	7	1
	Importance of Advantage	87.14	100.00	100.00	61.43	61.43	87.14	74.29	22.86	74.29	87.14	10.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better	**Atribute:**	5.5	2.25	2.25	6.5	7	11	8.75	8.75	8.75	2.75	2.75
	Advantage:	21.75	25	25	20.75	20.25	16.25	18.5	18.5	18.5	24.5	24.5
	Importance of Advantage	79.05	90.00	90.00	75.68	74.00	60.53	68.11	68.11	68.11	88.32	88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail]	**Atribute:**	2	2	2	7	2	7	7	9	4	2	5
	Advantage:	8	8	8	3	8	3	3	1	6	8	5
	Importance of Advantage	75.63	75.63	75.63	28.75	75.63	28.75	28.75	10.00	56.88	75.63	47.50
Factor: Number of movable parts **Criteria:** Lesser is better	**Atribute:**	4	3	5	6	4	4	5	4	5	3	6
	Advantage:	4	5	3	2	4	4	3	4	3	5	2
	Importance of Advantage	50.00	60.00	40.00	30.00	50.00	50.00	40.00	50.00	40.00	60.00	30.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better	**Atribute:**	18	13	15	42	38	33	37	25	37	23	19
	Advantage:	24	29	27	0	4	9	5	17	5	19	23
	Importance of Advantage	66.00	80.00	74.40	0.00	10.00	24.00	12.80	46.40	12.80	52.00	63.20
	Aggregate importance of advantages	358	406	380	196	271	250	224	197	252	363	239

Type 11

Factor / Criteria	Alternative 1 2.1 Flexiguard		Alternative 2 3.1 C-Clamp CC120		Alternative 3 3.3 MCC-130		Alternative 4 4.3 Alligator		Alternative 5 4.4 Parapet Clamp		Alternative 6 4.5 Parapet Anchor		Alternative 7 5.1 RaptorRail		Alternative 8 5.2 All-in-One		Alternative 9 5.3 UGPC		Alternative 10 8.1 - GRS-P12		Alternative 11 8.3 QR-P12	
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	3		2		2		5		5		3		4		8		4		3		9	
Advantage:	7		8		8		5		5		7		6		2		6		7		1	
Importance of Advantage		87.14		100.00		100.00		61.43		61.43		87.14		74.29		22.86		74.29		87.14		10.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	5.5		2.25		2.25		6.5		7		13		8.5		8.5		8.75		2.75		2.75	
Advantage:	21.75		25		25		20.75		20.25		14.25		18.75		18.75		18.5		24.5		24.5	
Importance of Advantage		79.05		90.00		90.00		75.68		74.00		53.79		68.95		68.95		68.11		88.32		88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	2		2		2		7		2		7		7		9		4		2		5	
Advantage:	8		8		8		3		8		3		3		1		6		8		5	
Importance of Advantage		75.63		75.63		75.63		28.75		75.63		28.75		28.75		10.00		56.88		75.63		47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	4		3		5		6		4		4		5		4		5		3		6	
Advantage:	4		5		3		2		4		4		3		4		3		5		2	
Importance of Advantage		50.00		60.00		40.00		30.00		50.00		50.00		40.00		50.00		40.00		60.00		30.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18		13		15		42		38		33		37		25		37		23		19	
Advantage:	24		29		27		0		4		9		5		17		5		19		23	
Importance of Advantage		66.00		80.00		74.40		0.00		10.00		24.00		12.80		46.40		12.80		52.00		63.20
Aggregate importance of advantages		358		406		380		196		271		244		225		198		252		363		239

Type 14-2

	Alternative 1 2.1 Flexiguard		Alternative 2 3.1 C-Clamp CC120		Alternative 3 3.3 MCC-130		Alternative 4 4.3 Alligator		Alternative 5 4.4 Parapet Clamp		Alternative 6 4.5 Parapet Anchor		Alternative 7 5.1 RaptorRail		Alternative 8 5.2 All-in-One		Alternative 9 5.3 UGPC		Alternative 10 8.1 - GRS-P12		Alternative 11 8.3 QR-P12	
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	3		3		3		5		5		3		4		8		4		3		9	
Advantage:	7		7		7		5		5		7		6		2		6		7		1	
Importance of Advantage		87.14		87.14		87.14		61.43		61.43		87.14		74.29		22.86		74.29		87.14		10.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	5.5		6		6		6.5		6.75		14		8.75		8.75		8.75		2.75		2.75	
Advantage:	21.75		21.25		21.25		20.75		20.5		13.25		18.5		18.5		18.5		24.5		24.5	
Importance of Advantage		79.05		77.37		77.37		75.68		74.84		50.42		68.11		68.11		68.11		88.32		88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	4		4		4		8		4		8		8		10		8		4		10	
Advantage:	6		6		6		2		6		2		2		0		2		6		0	
Importance of Advantage		56.88		56.88		56.88		19.38		56.88		19.38		19.38		0.00		19.38		56.88		0.00
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	4		3		5		6		4		4		5		4		5		3		6	
Advantage:	4		5		3		2		4		4		3		4		3		5		2	
Importance of Advantage		50.00		60.00		40.00		30.00		50.00		50.00		40.00		50.00		40.00		60.00		30.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18		13		15		42		38		33		37		25		37		23		19	
Advantage:	24		29		27		0		4		9		5		17		5		19		23	
Importance of Advantage		66.00		80.00		74.40		0.00		10.00		24.00		12.80		46.40		12.80		52.00		63.20
Aggregate importance of advantages		339		361		336		186		253		231		215		187		215		344		192

Type 22

	Alternative 1 2.1 Flexiguard	Alternative 2 3.1 C-Clamp CC120	Alternative 3 3.3 MCC-130	Alternative 4 4.3 Alligator	Alternative 5 4.4 Parapet Clamp	Alternative 6 4.5 Parapet Anchor	Alternative 7 5.1 RaptorRail	Alternative 8 5.2 All-in-One	Alternative 9 5.3 UGPC	Alternative 10 8.1 - GRS-P12	Alternative 11 8.3 QR-P12
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	7	7	7	8	8	7	8	10	7	7	10
Advantage:	3	3	3	2	2	3	2	0	3	3	0
Importance of Advantage	35.71	35.71	35.71	22.86	22.86	35.71	22.86	0.00	35.71	35.71	0.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	23.00	2.25	2.25	6.5	6.75	14	8.75	8.75	8.75	2.75	2.75
Advantage:	4.25	25	25	20.75	20.5	13.25	18.5	18.5	18.5	24.5	24.5
Importance of Advantage	20.11	90.00	90.00	75.68	74.84	50.42	68.11	68.11	68.11	88.32	88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	8	8	8	9	8	9	8	10	8	8	9
Advantage:	2	2	2	1	2	1	2	0	2	2	1
Importance of Advantage	19.38	19.38	19.38	10.00	19.38	10.00	19.38	0.00	19.38	19.38	10.00
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	5	4	6	7	5	5	6	5	6	4	7
Advantage:	3	4	2	1	3	3	2	3	2	4	1
Importance of Advantage	40.00	50.00	30.00	20.00	40.00	40.00	30.00	40.00	30.00	50.00	20.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18	13	15	42	38	33	37	25	37	23	19
Advantage:	24	29	27	0	4	9	5	17	5	19	23
Importance of Advantage	66.00	80.00	74.40	0.00	10.00	24.00	12.80	46.40	12.80	52.00	63.20
Aggregate importance of advantages	181	275	249	129	167	160	153	155	166	245	182

Type 23

	Alternative 1 2.1 Flexiguard	Alternative 2 3.1 C-Clamp CC120	Alternative 3 3.3 MCC-130	Alternative 4 4.3 Alligator	Alternative 5 4.4 Parapet Clamp	Alternative 6 4.5 Parapet Anchor	Alternative 7 5.1 RaptorRail	Alternative 8 5.2 All-in-One	Alternative 9 5.3 UGPC	Alternative 10 8.1 - GRS-P12	Alternative 11 8.3 QR-P12
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	9	7	7	10	10	7	8	9	8	8	9
Advantage:	1	3	3	0	0	3	2	1	2	2	1
Importance of Advantage	10.00	35.71	35.71	0.00	0.00	35.71	22.86	10.00	22.86	22.86	10.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	27.25	7.75	7.75	8	8.25	18.25	10.25	8.75	12.25	4.5	4.5
Advantage:	0	19.5	19.5	19.25	19	9	17	18.5	15	22.75	22.75
Importance of Advantage	0.00	71.47	71.47	70.63	69.79	36.11	63.05	68.11	56.32	82.42	82.42
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	5	5	5	10	10	7	7	9	5	5	5
Advantage:	5	5	5	0	0	3	3	1	5	5	5
Importance of Advantage	47.50	47.50	47.50	0.00	0.00	28.75	28.75	10.00	47.50	47.50	47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	5	4	6	8	6	5	6	4	6	4	7
Advantage:	3	4	2	0	2	3	2	4	2	4	1
Importance of Advantage	40.00	50.00	30.00	0.00	30.00	40.00	30.00	50.00	30.00	50.00	20.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18	13	15	42	38	33	37	25	37	23	19
Advantage:	24	29	27	0	4	9	5	17	5	19	23
Importance of Advantage	66.00	80.00	74.40	0.00	10.00	24.00	12.80	46.40	12.80	52.00	63.20
Aggregate importance of advantages	164	285	259	71	110	165	157	185	169	255	223

Type 25

	Alternative 1 2.1 Flexiguard		Alternative 2 3.1 C-Clamp CC120		Alternative 3 3.3 MCC-130		Alternative 4 4.3 Alligator		Alternative 5 4.4 Parapet Clamp		Alternative 6 4.5 Parapet Anchor		Alternative 7 5.1 RaptorRail		Alternative 8 5.2 All-in-One		Alternative 9 5.3 UGPC		Alternative 10 8.1 - GRS-P12		Alternative 11 8.3 QR-P12	
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	7		7		7		10		9		7		4		7		7		8		10	
Advantage:	3		3		3		0		1		3		6		3		3		2		0	
Importance of Advantage		35.71		35.71		35.71		0.00		10.00		35.71		74.29		35.71		35.71		22.86		0.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	26.75		7.75		7.75		8		8.25		17.75		8.75		8.75		10.25		4.25		4.25	
Advantage:	0.5		19.5		19.5		19.25		19		9.5		18.5		18.5		17		23		23	
Importance of Advantage		7.47		71.47		71.47		70.63		69.79		37.79		68.11		68.11		63.05		83.26		83.26
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	3		3		3		10		10		7		7		9		5		3		5	
Advantage:	7		7		7		0		0		3		3		1		5		7		5	
Importance of Advantage		66.25		66.25		66.25		0.00		0.00		28.75		28.75		10.00		47.50		66.25		47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	5		4		6		8		6		5		5		4		6		4		7	
Advantage:	3		4		2		0		2		3		3		4		2		4		1	
Importance of Advantage		40.00		50.00		30.00		0.00		30.00		40.00		40.00		50.00		30.00		50.00		20.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18		13		15		42		38		33		37		25		37		23		19	
Advantage:	24		29		27		0		4		9		5		17		5		19		23	
Importance of Advantage		66.00		80.00		74.40		0.00		10.00		24.00		12.80		46.40		12.80		52.00		63.20
Aggregate importance of advantages		215		303		278		71		120		166		224		210		189		274		214

Type 31

	Alternative 1 2.1 Flexiguard	Alternative 2 3.1 C-Clamp CC120	Alternative 3 3.3 MCC-130	Alternative 4 4.3 Alligator	Alternative 5 4.4 Parapet Clamp	Alternative 6 4.5 Parapet Anchor	Alternative 7 5.1 RaptorRail	Alternative 8 5.2 All-in-One	Alternative 9 5.3 UGPC	Alternative 10 8.1 - GRS-P12	Alternative 11 8.3 QR-P12
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	3	2	2	5	5	3	4	8	4	3	9
Advantage:	7	8	8	5	5	7	6	2	6	7	1
Importance of Advantage	87.14	100.00	100.00	61.43	61.43	87.14	74.29	22.86	74.29	87.14	10.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	5.5	2.25	2.25	6.5	7	12	8.75	8.75	8.75	2.75	2.75
Advantage:	21.75	25	25	20.75	20.25	15.25	18.5	18.5	18.5	24.5	24.5
Importance of Advantage	79.05	90.00	90.00	75.68	74.00	57.16	68.11	68.11	68.11	88.32	88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	2	2	2	7	2	7	7	9	4	2	5
Advantage:	8	8	8	3	8	3	3	1	6	8	5
Importance of Advantage	75.63	75.63	75.63	28.75	75.63	28.75	28.75	10.00	56.88	75.63	47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	4	3	5	6	4	4	5	4	5	3	6
Advantage:	4	5	3	2	4	4	3	4	3	5	2
Importance of Advantage	50.00	60.00	40.00	30.00	50.00	50.00	40.00	50.00	40.00	60.00	30.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18	13	15	42	38	33	37	25	37	23	19
Advantage:	24	29	27	0	4	9	5	17	5	19	23
Importance of Advantage	66.00	80.00	74.40	0.00	10.00	24.00	12.80	46.40	12.80	52.00	63.20
Aggregate importance of advantages	358	406	380	196	271	247	224	197	252	363	239

Type 32

	Alternative 1		Alternative 2		Alternative 3		Alternative 4		Alternative 5		Alternative 6		Alternative 7		Alternative 8		Alternative 9		Alternative 10		Alternative 11	
	2.1 Flexiguard		3.1 C-Clamp CC120		3.3 MCC-130		4.3 Alligator		4.4 Parapet Clamp		4.5 Parapet Anchor		5.1 RaptorRail		5.2 All-in-One		5.3 UGPC		8.1 - GRS-P12		8.3 QR-P12	
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest **Atribute:**	7		7		7		8		9		7		4		7		7		8		10	
Advantage:	3		3		3		2		1		3		6		3		3		2		0	
Importance of Advantage		35.71		35.71		35.71		22.86		10.00		35.71		74.29		35.71		35.71		22.86		0.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better **Atribute:**	23.5		3.75		3.75		8		8.25		12		8.75		8.75		8.75		2.75		2.75	
Advantage:	3.75		23.5		23.5		19.25		19		15.25		18.5		18.5		18.5		24.5		24.5	
Importance of Advantage		18.42		84.95		84.95		70.63		69.79		57.16		68.11		68.11		68.11		88.32		88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail] **Atribute:**	3		3		3		7		10		7		7		9		5		3		5	
Advantage:	7		7		7		3		0		3		3		1		5		7		5	
Importance of Advantage		66.25		66.25		66.25		28.75		0.00		28.75		28.75		10.00		47.50		66.25		47.50
Factor: Number of movable parts **Criteria:** Lesser is better **Atribute:**	5		4		6		7		6		5		5		4		6		4		7	
Advantage:	3		4		2		1		2		3		3		4		2		4		1	
Importance of Advantage		40.00		50.00		30.00		20.00		30.00		40.00		40.00		50.00		30.00		50.00		20.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better **Atribute:**	18		13		15		42		38		33		37		25		37		23		19	
Advantage:	24		29		27		0		4		9		5		17		5		19		23	
Importance of Advantage		66.00		80.00		74.40		0.00		10.00		24.00		12.80		46.40		12.80		52.00		63.20
Aggregate importance of advantages		226		317		291		142		120		186		224		210		194		279		219

Type 33

		Alternative 1 2.1 Flexiguard	Alternative 2 3.1 C-Clamp CC120	Alternative 3 3.3 MCC-130	Alternative 4 4.3 Alligator	Alternative 5 4.4 Parapet Clamp	Alternative 6 4.5 Parapet Anchor	Alternative 7 5.1 RaptorRail	Alternative 8 5.2 All-in-One	Alternative 9 5.3 UGPC	Alternative 10 8.1 - GRS-P12	Alternative 11 8.3 QR-P12
Factor: Ease of installation and mobilty **Criteria:** 1 - 10 with 1 being the easiest	**Atribute:**	7	7	7	8	9	7	4	7	7	8	10
	Advantage:	3	3	3	2	1	3	6	3	3	2	0
	Importance of Advantage	35.71	35.71	35.71	22.86	10.00	35.71	74.29	35.71	35.71	22.86	0.00
Factor: Intrusion into the work area [measured in inches] **Criteria:** Lesser is better	**Atribute:**	23.5	3.75	3.75	8	8.25	12	8.75	8.75	8.75	2.75	2.75
	Advantage:	3.75	23.5	23.5	19.25	19	15.25	18.5	18.5	18.5	24.5	24.5
	Importance of Advantage	18.42	84.95	84.95	70.63	69.79	57.16	68.11	68.11	68.11	88.32	88.32
Factor: Exposure to unprotected edge **Criteria:** Lesser is better [1-5 not going over the rail. And 6-10 over the rail]	**Atribute:**	1	1	1	2	2	2	2	2	1	1	2
	Advantage:	9	9	9	8	8	8	8	8	9	9	8
	Importance of Advantage	85.00	85.00	85.00	75.63	75.63	75.63	75.63	75.63	85.00	85.00	75.63
Factor: Number of movable parts **Criteria:** Lesser is better	**Atribute:**	5	4	6	7	6	5	5	4	6	4	7
	Advantage:	3	4	2	1	2	3	3	4	2	4	1
	Importance of Advantage	40.00	50.00	30.00	20.00	30.00	40.00	40.00	50.00	30.00	50.00	20.00
Factor: Weight [measured in lbs.] **Criteria:** Lesser is better	**Atribute:**	18	13	15	42	38	33	37	25	37	23	19
	Advantage:	24	29	27	0	4	9	5	17	5	19	23
	Importance of Advantage	66.00	80.00	74.40	0.00	10.00	24.00	12.80	46.40	12.80	52.00	63.20
Aggregate importance of advantages		245	336	310	189	195	232	271	276	232	298	247

Appendix F – Field Survey Questionnaire

SURVEY QUESTIONNAIRE

Date: ________/_______/________

Location: ____

DEMOGRAPHICS

1. Identify your gender:
Check one:
- ○ Male
- ○ Female
- ○ Prefer not to answer

2. **How many years of experience do you have in roadway construction or maintenance?**

☐☐

3. What is your age group?
Check one:
- ○ Under 18
- ○ 18 – 24
- ○ 25 – 34
- ○ 35 – 44
- ○ 45 – 54
- ○ 55 – 64
- ○ 65 – 74
- ○ 74 – 84
- ○ 85 or older

4. Have you used Fall Protection Supplementary Devices (e.g., BuckRail, RaptorRail) in the past?

Check one:
- ○ Yes
- ○ No

Fall Protection Supplementary Devices (FPSD) INSTALLATIONS

5. **Which FPSD did you install today?**
Select all that apply:

- ○ Fall Protection Systems – CC120
- ○ Fall Protection Systems – MCC130
- ○ Ellis Manufacturing – GRS-P12
- ○ AES Raptor – RaptorRail
- ○ BlueWater Manufacturing – ParaClamp
- ○ Other (1). Please specify: ____
- ○ Other (2). Please specify: ____

****The survey continues in the next page****

6. For each of the Fall Protection Supplementary Device (FPSD) you have used today, please indicate your level of agreement with each statement below in a scale from (1) for strong disagreement to (7) for strong agreement.

Statement	CC120	MCC130	RaptorRail	ParaClamp	GRS-P12	Other (1)	Other (2)
a. The FPSD feels lightweight and its installation and uninstallation requires acceptable physical effort (i.e., does not require overexertion).							
b. The FPSD is easy to install and uninstall to and from the guardrail.							
c. The FPSD can be quickly installed and uninstalled to and from the guardrail.							
d. The installed FPSD does not interfere with bridge maintenance and inspection operations.							
e. The FPSD is easy to load and unload from work vehicles and to carry around the work area.							
f. The FPSD is compact and requires minimal storage space in the yard/warehouse.							
g. The FPSD appears durable, sturdy, and requires minimal maintenance.							
h. Learning to use the FPSD is quick, intuitive, and does not require extensive instruction.							
i. The FPSD requires minimal preparation before installation.							
j. When installed, the FPSD increases the likelihood of struck-against incidents (i.e. protrusion into the work area).							
k. The installation does not require me to overextend beyond the bridge guardrail.							
l. The installation does not require me to be in uncomfortable postures (e.g. kneeling, bending) for extended time periods.							
m. The risk of hand injuries while handling the FPSD is minimal (e.g., cuts from sharp ends, pinch points).							
n. The FPSD effectively reduces the risk of falls from bridge decks.							
o. I would recommend the use of this FPSD during bridge work.							

****The survey continues in the next page****

7. If you could select only one Fall Protection Supplementary Device (FPSD), which of the following would you choose?

Choose one:

- ○ Fall Protection Systems – CC120
- ○ Fall Protection Systems – MCC130
- ○ Ellis Manufacturing – GRS-P12
- ○ AES Raptor – RaptorRail
- ○ BlueWater Manufacturing – ParaClamp
- ○ Other (1). Please specify: ____
- ○ Other (2). Please specify: ____

8. Please explain why you chose the FPSD from the previous question as your preferred alternative:

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Thank you for your responses.