HYDRAULICS AND HIGHWAY ENGINEERING

By

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Presented at

Henry M. Shaw Lecture Series
in Civil Engineering

North Carolina State University
Raleigh, N. C.
December 11, 1968

Your invitation to participate in the Henry M. Shaw Lecture Series is indeed a pleasure and honor. It is especially gratifying that hydraulics as related to highway engineering is to be included in this series.

When I mention hydraulics, several thoughts might come to your mind as to specific topics that might be discussed. Depending upon your background in school or your experience working in the profession, you could have different impressions of the subject. Most of you will associate the word hydraulics with water, but being engineers such specific fields as dams, reservoirs, water supply and irrigation systems will come to mind. I hope that after my discussion this evening you will realize hydraulics has a place in highway engineering too.

Highway engineering today is one of the broadest fields of civil engineering. It provides a wide range of employment opportunities, both in working conditions and technical specialities. There are jobs for the introvert and the extrovert, the indoor type and the outdoor type. Since roads are needed everywhere you can usually pick your climate even to the extent of working in a foreign country. You can work for a public agency, private industry or even establish your own consulting firm or contracting business. You can work in research, design, construction or maintenance and become involved in either administration or some technical field. What a choice the young civil engineer has today when he selects highway engineering as his life work!

After such a broad picture of highway engineering some of you will conclude that hydraulic applications must be highly specialized and of minor importance. Nothing could be further from the truth. Problems related to water cut across all phases of highway work - from negotiating for right-of-way to the actual design, construction and maintenance of drainage structures. Last year this country spent about eight billion dollars on the construction of all highways, including minor roads and streets. About three billion dollars of this total was spent on the interstate system of highways. Our figures indicate that about 10 percent of this construction money is spent on bridges over streams and 7.5 percent for other drainage facilities such as street inlets, storm sewers, channels, small culverts, etc. Applying these percentages, we spend about 1.4 billion dollars annually on drainage structures. To avoid any false impression as to the importance of hydraulics and before my colleaques involved in geometrics, structures, traffic and the many other phases of highway engineering, question my enthusiasm, I will be the first to admit that their contribution to the highway program is important too. It takes many types of specialists to build a highway but to ignore the effects of water would be disasterous.

It would be foolhardy for me to attempt a discussion tonight to all the hydraulic principles and water related problems that we encounter in highway work. I have chosen instead to select a few important topics that might be of interest to you and will serve to illustrate how hydraulics fits into highway engineering. I will do this with the aid of a few slides. (Several photos used in this presentation are appended at the end of this paper).

History of Highway Drainage

Fifty years ago or even more recently in some areas, poor road drainage was tolerated as a fact of life. The old mud engineer was like the farmer who would not admit he was so stupid that he did not know how to mix concrete. Culverts and bridges were sized by one of the older flood formulas, high-water marks or judgement. Washouts or flooded roads did not cause much criticism from the public because most new construction was much superior to the old wagon trails. With the advent of the high-speed automobile and more need for rapid transportation, drainage became more of a problem for the engineer. The once economical bridge that crossed a gorge carrying a small stream is being replaced by huge fills and culverts. Methods of construction and design standards have changed tremendously. Earth moving equipment has improved and labor has become expensive. Water problems have become more critical and many of the solutions are quite complex.

Floods

When we speak of hydraulics, floods are always of primary concern to the highway engineer. We all want our structures to pass flood water without damage. Evaluating or estimating a flood is one of the most difficult problems that confronts us today.

Structural engineers design a bridge for truck loadings using factors of safety. After construction, their bridge is further protected from failure by overloads with various controls including weighing stations and load limit signs. Can the hydraulic engineer use flood limit signs to protect his structure! Safety factors will not save a structure if the meteorologic conditions decide to produce an unusual flood. And, we have not lived long enough to experience that unusual or "super flood" on all streams!

In recent years we have stressed the use of flood frequency analysis for estimating floods. That is, we try to estimate floods from our past flood experience. The U. S. Geological Survey and the various State highway departments, including North Carolina, have done much work on this subject and have given the designer a better means of estimating floods on our streams than has been available in the years past. Much more work needs to be done both in collecting flood data and in developing a good procedure for analysis. In short, we are attempting to improve our flood estimating procedures. The Bureau of Public Roads now requires reports for the hydrologic and hydraulic design of drainage structures built on the Federal-aid system of highways.

Bridges

Yes, we do have problems with drainage structures because of our inability to estimate floods. Unfortunately, however, many of our failures are caused by reasons other than the structures being too small to carry flood flow. A washout of the fill at a bridge abutment or material under a pier does not necessarily mean a longer or higher bridge will solve the problem. The key to the solution is to determine how the water caused the damage and small floods can be as much of a problem as unusual floods.

If the roadway embankment blocks a portion of the flood plain flow, our field observations and laboratory tests tell us that spur dikes placed at a bridge abutment will guide and direct the flow past the abutment and minimize erosion or scour. A movie showing this dike and its operation in the field and laboratory has recently been made by the Bureau of Public Roads. It may be borrowed free of charge from our Washington Office.

Scour at piers is another main cause of bridge failures. Depth of foundations and orientation of piers with respect to flow are fundamental in the design of any bridge against the ravages of floods. Many engineers believe that piling will save any bridge. Yes, they will if there are enough of them of sufficient length and proper design to resist the forces created in a flood, scour and drift included. Driving piles for load bearing is not sufficient. Piling must be long enough to extend beyond scour depths, and of a design which provides lateral stability. Prediction of scour depths is difficult and at present is usually estimated by the results obtained from model investigations. We are striving to accumulate scour data at several bridge sites to verify our procedures.

Because of the chance of a flood occurring that exceeds our design flood, some consideration should be given to the possible consequences. This should be true in the case of bridge design in particular since replacement of a bridge takes considerable time and money. We can learn an object lesson from the old bridge builders who constructed overflow bridges or lowered the approach embankment to pass flood water. Some of our designs today are based on this concept. Special precautions must be taken, however, in both the hydraulic and structural aspects of the design to have the crossing function properly. Flotation of structures, scour and embankment erosion and the duration of the flood are primary factors to be considered. To avoid the implication that I am promoting a design that causes flooding of a highway, I would like to add that the crossing geometry, including the bridge opening, can usually be adjusted to accommodate any desired flood.

Culverts

As I indicated previously, culverts are becoming both practical and economical for many locations where several years ago we would have built a bridge. The location, the stream hydrology and the hydraulics of the structure itself require more attention because of the high cost of the installation and the potential flood hazard.

It is no disgrace to have one of our culverts so small that it forces an unusual flood over the roadway especially when it does not result in a failure. Certainly, if this flooding happens too often, the traveling public will criticize us. What should concern us more is to have a culvert washout or fail when the road is not overtopped. This type of failure deserves our attention.

Good bedding and backfilling are important for the structural stability of a culvert. We must, however, be careful that our granular backfill and bedding materials do not allow water to flow along the culvert barrel and carry away supporting materials, causing washouts and eventual failure of the culvert. Water flowing under corrugated metal pipe arches has created hydraulic pressure sufficient to buckle the bottom plates upward. A good headwall or slope paving and an impervious backfill at the entrance will help prevent this type of failure and yet permit the use of granular material for bedding and backfill. Sometimes when drainage or seepage water enters along the length of a culvert, a separate subdrainage system might be required.

Some culvert entrances are particularly vulnerable to failure from hydraulic forces. Projecting inlets of corrugated metal culverts have been buoyed up causing water to pond against embankments and, in some cases, washouts. Mitered or step beveled inlets on metal pipe have also collapsed from lack of support against the forces of water and debris. Although large floods are usually the cause of such entrance failures, lesser floods have caused failures too. Many of these inlet failures can be avoided if the culvert is properly designed, considering the material used and the hydraulic and other forces acting upon it.

In providing a culvert entrance that will resist hydraulic forces, it is often possible to improve its hydraulic efficiency at the same time. Such improvements are especially desirable for long culverts on steep grades because the bottle-neck or control of the flow is at the inlet. Without defining a long culvert or a steep grade, let it suffice to say that the longer the culvert and the steeper the grade the greater are the chances of increasing capacity or decreasing cost by improving the inlet. The Bureau of Public Roads in cooperation with the National Bureau of Standards has done considerable research on this subject, and several States, including North Carolina, have constructed culverts based on the principles developed by this research. Whether a special or conventional design, some engineers are concerned about possible clogging of the culvert inlet with debris. To reduce the risk of clogging, debris-control structures of various types are coming into common use, thus avoiding construction of a structure with an opening larger than necessary to carry the floodwater.

Erosion at culvert outlets is a problem almost everywhere. By the very nature of the structure, a culvert increases velocities above those in the natural stream causing some erosion in the outlet channel. This problem is most serious with concrete structures, especially sectional concrete pipe, because each section drops off in turn until the roadway shoulder is undercut and loses its support or the entire culvert and embankment fails. Various types of energy dissipators have been used to reduce culvert outlet velocities. These devices are expensive and the designer must weigh the degree of protection needed before building them. We are in search for a more economical method of solving this problem.

Erosion Control and Safety

At the present time roadside beautification and safety are receiving much emphasis. Erosion scars and sediment deposits along our highways certainly detract from their beauty and often present a safety hazard. Usually good hydraulic design and erosion control measures are compatible with good landscaping practice and safety standards. Channel configurations with moderately flat side slopes and wide bottoms offer a minimum hazard to a vehicle out of control, yet serve well as a hydraulic facility. Large, deep gutters and hazardous structures should be avoided, especially in the roadway median or close to the roadway shoulder.

Some engineers believe that concrete channels solve all erosion problems. This is not necessarily true. A rigid channel is quite vulnerable to failure if it is not designed and constructed properly. Frost action and poor foundations cause displacement and cracks in rigid sections and eventual erosion of supporting soil. Also, the smooth surface of concrete channels creates high velocities which are difficult to control, especially at the channel outlet. Overtopping and undercutting of channel walls are quite common when we have what is termed supercritical flow. And we usually have supercritical flow in concrete channels when the slope is over 0.5 percent.

Other more economical and less vulnerable types of channel protection can often be used. The various types of protection must be studied and used with discretion. The U.S. Department of Agriculture Experimental Station at Stillwater, Oklahoma has done outstanding research in soil erosion prevention and channel protection by the use of vegetal cover. Briefly this testing tells us that a good stand of grass, whether it is started from seed or sod, is good protection against erosion in many locations - if we can get the grass to grow and then maintain it.

Grass can be an economical answer to many of our erosion problems. Too often we plant seed and then comes the rain. Topsoil and seed are washed away and our culverts are clogged with mud. Our erosion-prevention job could be called a complete failure. Our design was wrong for an area where we could reasonably expect a thunderstorm before the grass became well established. Maybe sod should have been used or some temporary protection should have been given to the seed and soil.

There is another type of lining that has been used rather extensively in some States. It consists of crushed rock. Some of you might call it a form or riprap. I believe this type of lining has a place, either where grass won't grow or where grass will not prevent erosion. Rock is generally cheaper than concrete, easier to maintain, and has a self-healing characteristic. Recent research at the University of Minnesota has developed a design method for rock-lined channels.

Ditch checks or grade-control structures have been used to prevent channel erosion. This can be done if proper structures are used. By this I mean structures that dissipate the energy of the flow, maintain non-erosive velocities and are of sufficient size to carry unusual floods. Too many ditch checks constructed in the past accelerate the flow and cause erosion. Without getting too far into a discussion of this subject, let us say that if we are going to build ditch checks that are properly designed, they will probably be more expensive and require more maintenance than other solutions.

When speaking of grass protection for our slopes and channels, there is always the fellow who says that grass will not grow in his area. True, there are locations where it is difficult or impossible to grow grass because of the lack of moisture or because of poor soil. To reduce embankment gullies, some States place shoulder curbs at critical locations and then install inlets along the curb to carry the collected water down the embankment slope in either an open or a closed channel. It has been our experience that closed corrugated metal pipe is the most satisfactory method for conveying water down embankment slopes.

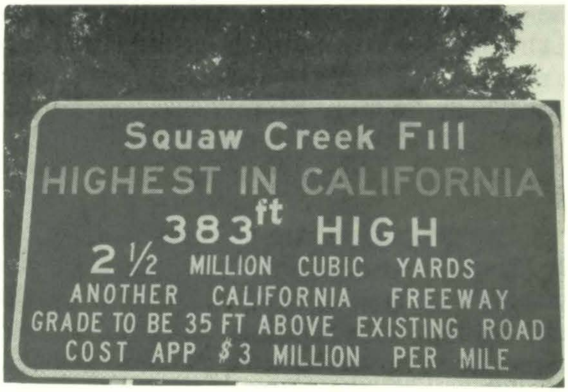
It is the engineer's job to determine the best method for controlling erosion in his area. What works in one section of your State might not be applicable in another section. I understand this University has a continuing research project on ditch lining and erosion control for the Highway Department.

Aside from the design of proper channel linings and adequate waterways, the importance of erosion control during construction cannot be overemphasized. If heavy rains fall before protection is provided, bare soil will erode to form deep gullies. These erosion scars are quite difficult to correct. Embankment and cut slopes should be protected at the earliest possible time after grading, and channels should be lined with the best and most economical erosion resistant material for your particular area and purpose. In this case, as in most hydraulic problems, an "ounce of prevention is worth a pound of correction"!

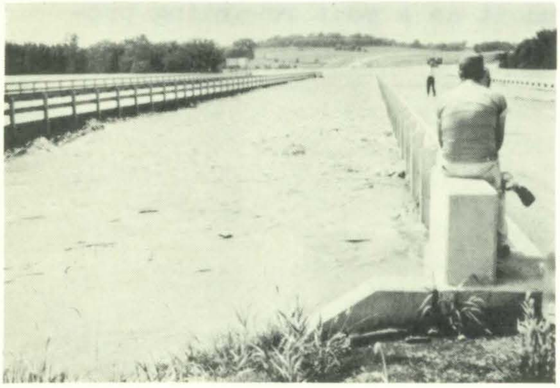
Conclusion

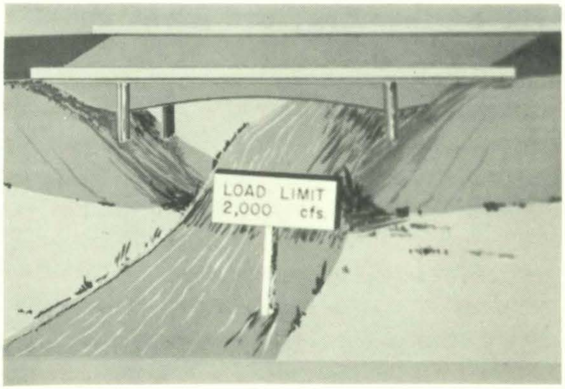
As I stated in the beginning, I have only been able to discuss a few of the hydraulic problems that we are concerned with in highway work. We could have mentioned storm sewers, pumping plants, dams and reservoirs, detention and recharge basins, river training works, channel changes, embankment protection, preservation of fish and wildlife habitat, control of pollution in streams during and after construction, and all the hydraulic principles and computations associated with each. Our problems related to hydraulics are numerous. In Public Roads we are attempting to develop design bulletins, charts and other tools to assist the designer. We are even developing computer programs to help reduce the work involved in making hydraulic computations.

Although many of these aids or tools are available, hydraulics is not a field for the handbook engineer. Our best tool in assuring adequate and economical hydraulic designs for our highways is a well-trained engineer - an engineer with a good background in engineering mechanics and hydraulic principles. The schools and professors who concentrate on the basic laws of science and develop in the student an ability to apply them are to be commended. We are just beginning to recognize many of the water associated engineering problems in our society. The opportunities for the young engineer in this field, whether it be in highways or some other works in civil engineering, are great and I recommend it as a most rewarding profession.

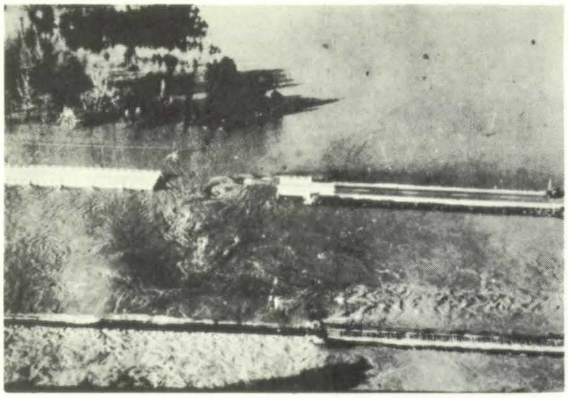


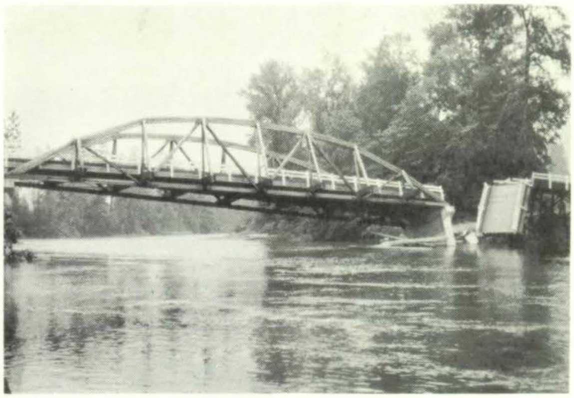
Culverts and high highway embankments are replacing bridges of yesteryear. Fill material from large cuts must be disposed of and present day equipment makes this type of construction economical. The hydraulic capacity of the culvert becomes an important part of design.



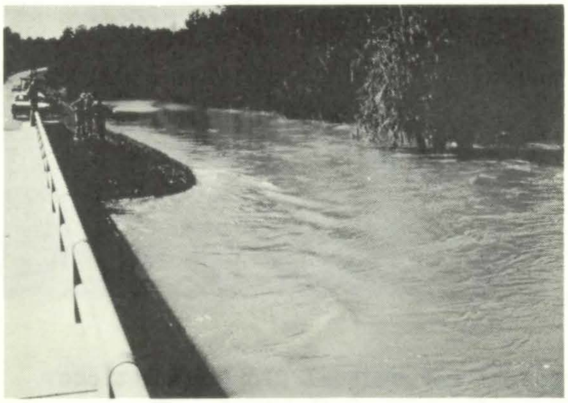


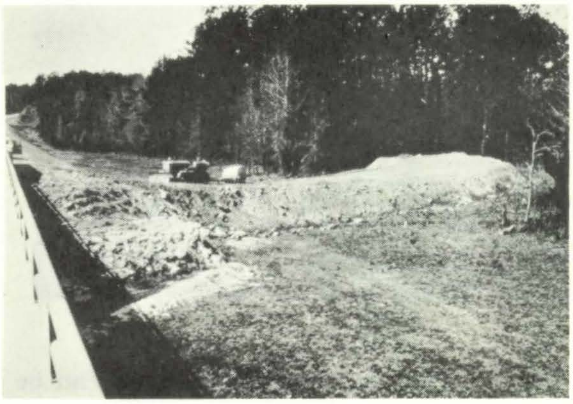
Stream hydrology is important in bridge design. A load limit sign will not save a structure!





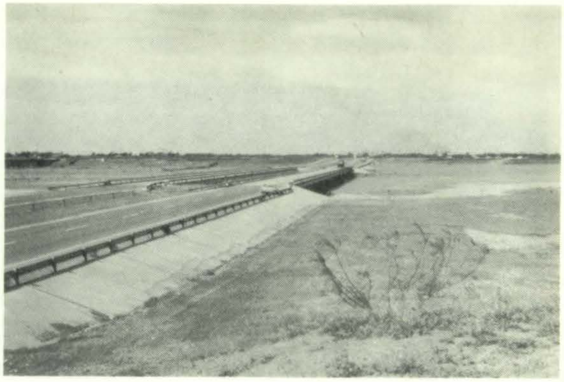
Scour of foundation material is the main cause for bridge failures. Adequate boring logs and an appreciation of the scour phenomena are necessary for proper design. Footing elevations and piling penetration should be specified.



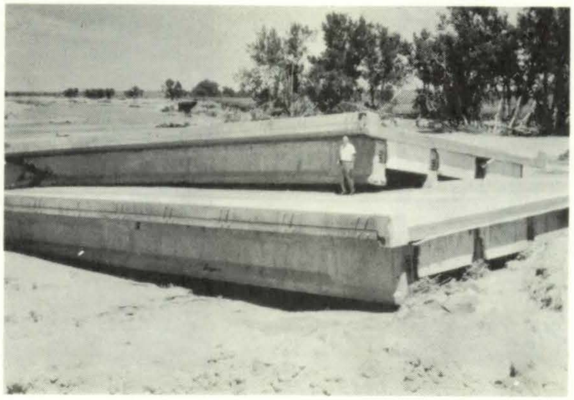


Where a quantity of river flow is diverted to a bridge from a flood plain by an approach embankment, a spur dike could prevent or minimize abutment and pier scour. Photos above are at the same location - with and without spur dike.

Bridge replacement is costly. Designs permitting unusual flood flow to cross approach fills has been used for many years, especially on minor roads where a detour is available and traffic count is low.

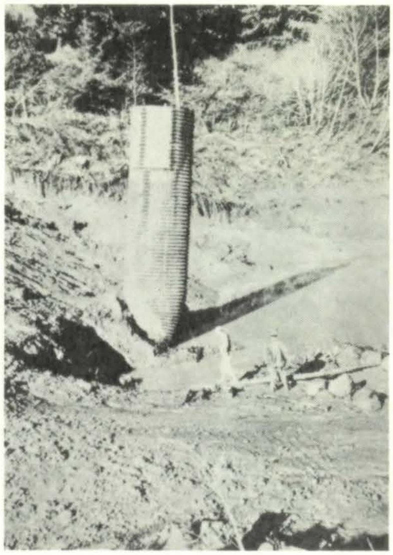


With proper design, bridges can be overtopped for unusual flood conditions. Photo at right shows bridge and embankment after flood shown in left picture had passed. No evidence of damage was observed.



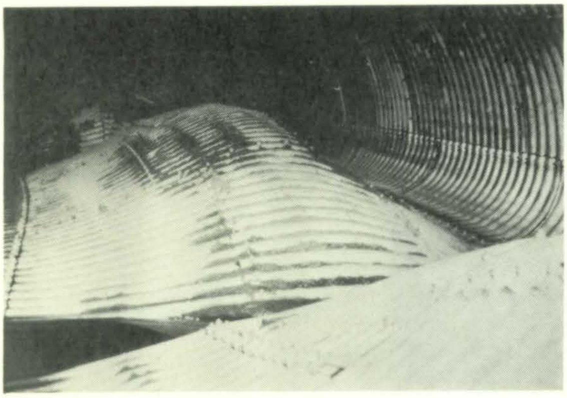
Concrete bridges will float! Air trapped under these 80 foot pretressed concrete spans and the force of the flood water against the girders carried these spans several hundred feet downstream from the substructure.

(a)

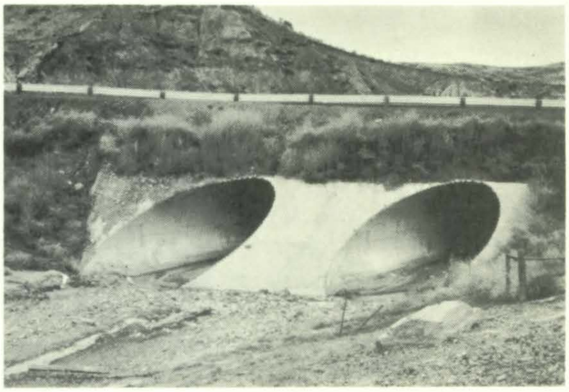


(b)

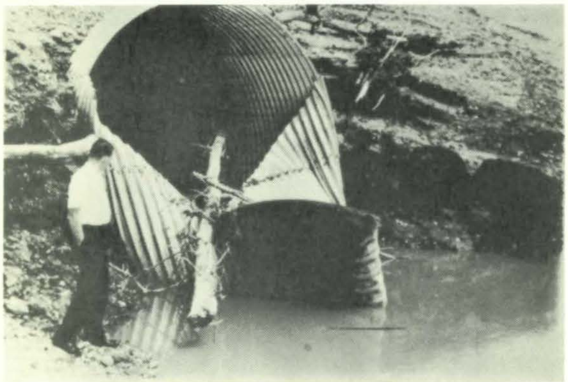
Metal pipes installed as projecting inlets (a) above can fail due to uplift caused by a contraction of flood flow at entrance and a resultant bouyant force. See Highway Research Board Bulletin 286, 1961, for report of such a failure, (b).



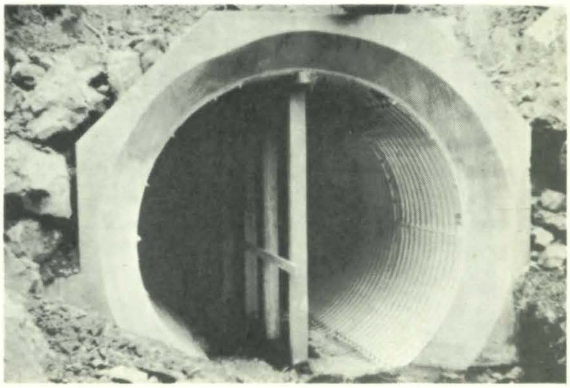
The hydrostatic force of water beneath this metal pipe arch lifted the bottom section at intervals throughout its length.



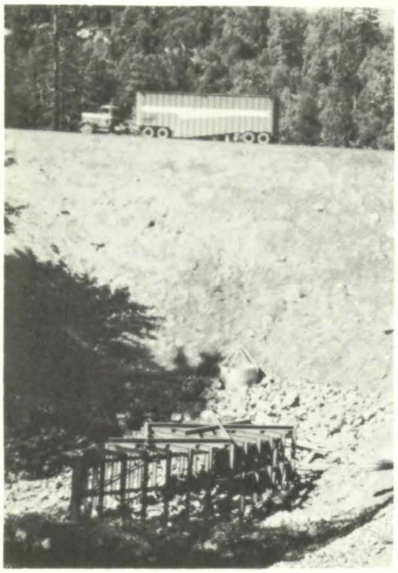
An external drainage system along the pipe, good headwalls and impervious material at the culvert entrance reduce the risk of failure from hydrostatic forces and piping.



Hydraulic forces and drift can damage culvert entrances if not designed properly.



A simple entrance design which secures the culvert entrance and improves hydraulic capacity.

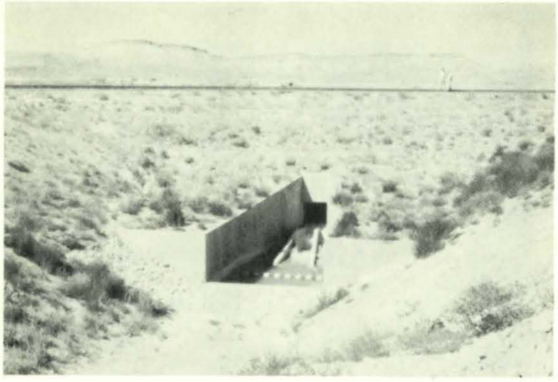


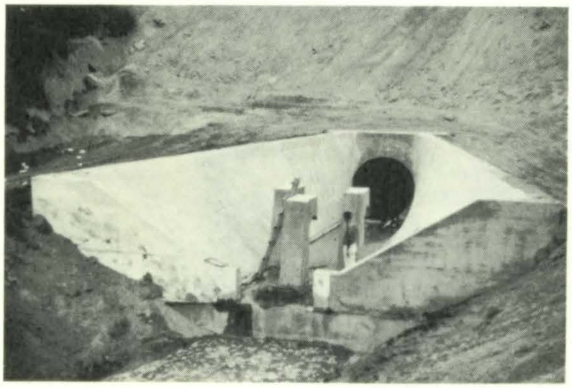
Debris rack and relief pipe prevents serious clogging at culvert entrances.

An improved culvert entrance which accelerates flow thus increasing capacity. Especially beneficial on long culverts on steep grades.

Sectional pipe is particularly vulnerable to scour at culvert outlet.

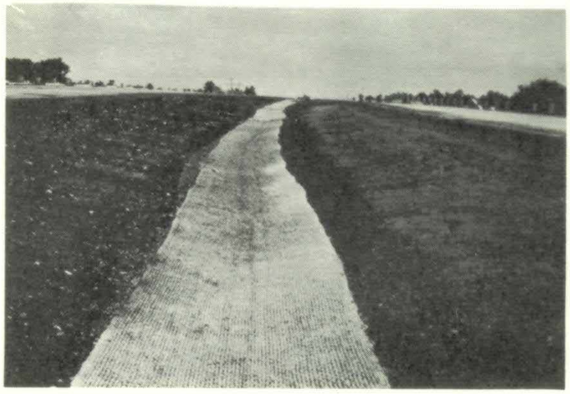
Impact type energy dissipator can be used to reduce scour at some culvert outlets.





Various types of energy dissipators have been used at culvert outlets to reduce channel erosion.

Severe erosion should be avoided both during and after construction to reduce sedimentation and safety hazards.

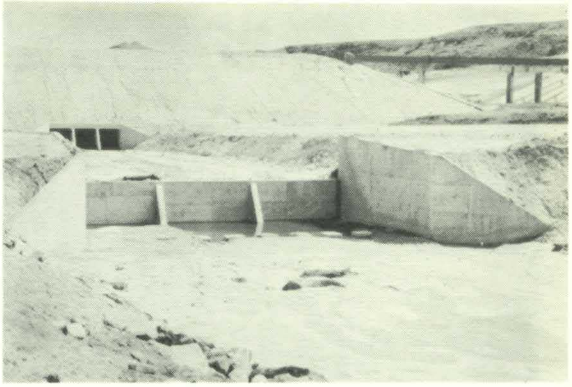


Temporary channel linings and the establishment of vegetation immediately after grading save construction dollars and minimizes erosion and stream pollution.

A Bermuda grass-lined channel will withstand considerable flow and velocity if well established.

Concrete channels are vulnerable to failure if not properly constructed.

Recent research has improved our methods for sizing riprap for rock-lined channels.



Drop structures and other types of grade control structures are used where channel grades are steep and soils are quite erosive.

Median inlets which present a safety hazard (left photo) should be avoided. Photo at right shows a flush type grate inlet with slots for small debris.

Fenced detention basins can be used to lower flood peaks and reduce costs for outlet structures.

A dike separating the clear river flow from a borrow pit area, thus avoiding damage to fish and their habitat.

River training works controlling the natural river meanders to fit the bridge location.

An Interstate highway embankment serves as a dam for a recreation reservoir. Built as a cooperative highway and recreation project.