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The Mendenhall Glacier and the Forest highway leading to it, Alaska.

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IN THIS ISSUE

TITLE SHEET, VOL. 33

The title sheet for vol. 33, Apr. 1964–Feb. 1966, of *PUBLIC ROADS, A Journal of Highway Research* is now available. This sheet contains a chronological list of article titles and an alphabetical list of authors' names. Copies of this title sheet can be obtained by a request to the editor of the magazine, Bureau of Public Roads, Washington, D.C., 20235.

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Effect of Soil Blankets and Preloading on Settlement

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

By EDWARD S. BARBER, Highway Research Engineer,[1] Materials Division

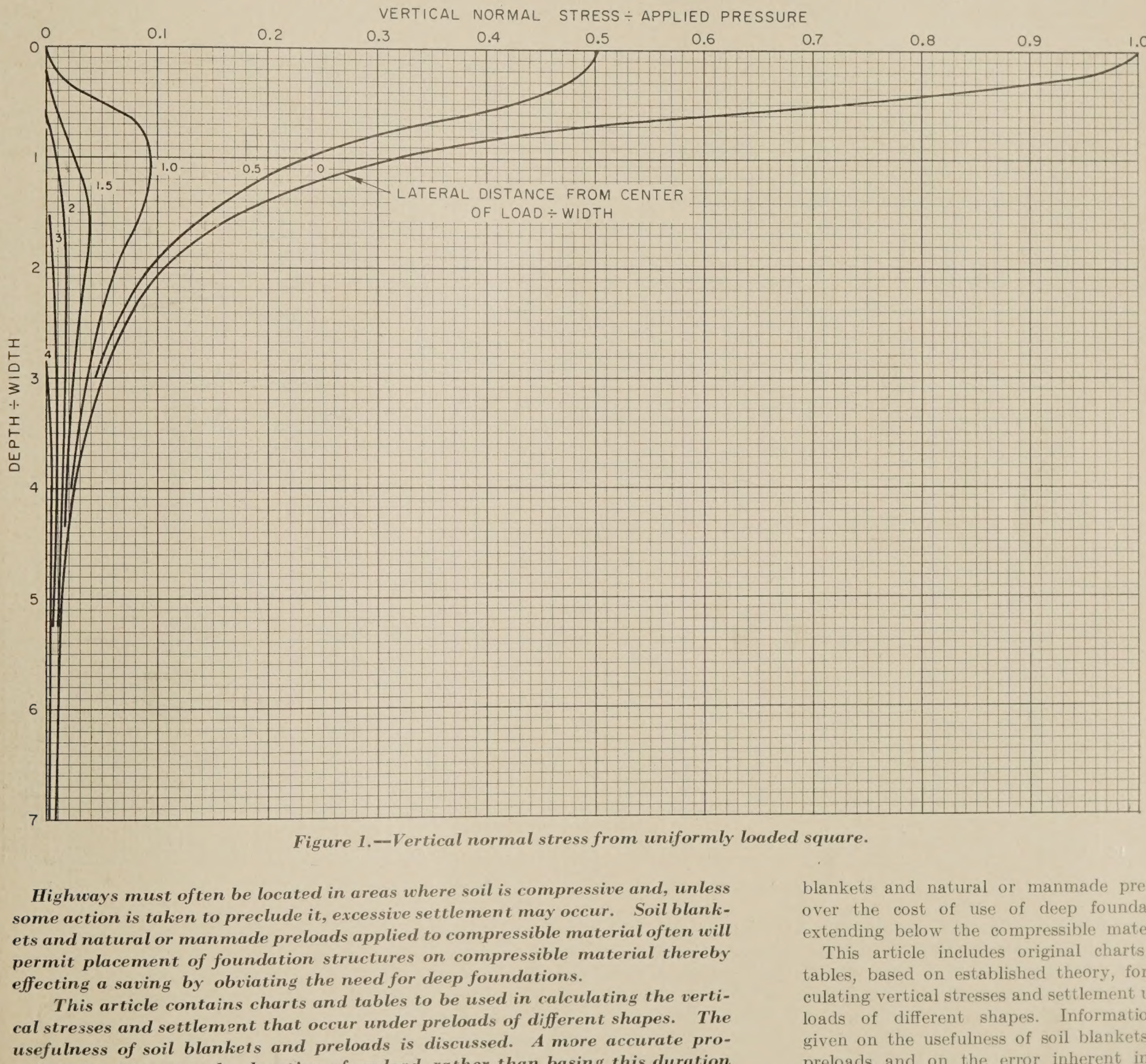


Figure 1.—Vertical normal stress from uniformly loaded square.

Highways must often be located in areas where soil is compressive and, unless some action is taken to preclude it, excessive settlement may occur. Soil blankets and natural or manmade preloads applied to compressible material often will permit placement of foundation structures on compressible material thereby effecting a saving by obviating the need for deep foundations.

This article contains charts and tables to be used in calculating the vertical stresses and settlement that occur under preloads of different shapes. The usefulness of soil blankets and preloads is discussed. A more accurate procedure for designing the duration of preload, rather than basing this duration on average consolidation, also is presented.

Introduction

FOUNDATION structures can be placed on compressible soil materials without excessive settlement if the applied stresses do not significantly exceed the stresses previously imposed on the material. A blanket of relatively incompressible soil can be used over compressible material to spread the foundation load and thereby reduce the imposed stresses, and a temporary overload on the compressible material can be used to consolidate or prestress it. A considerable cost saving has been made by the use of soil blankets and natural or manmade preloads over the cost of use of deep foundations extending below the compressible materials.

This article includes original charts and tables, based on established theory, for calculating vertical stresses and settlement under loads of different shapes. Information is given on the usefulness of soil blankets and preloads and on the error inherent in the practice of basing preload duration on average consolidation. Also, a more accurate procedure for designing preload duration is described.

Conclusion

On the basis of information presented in this article, it is concluded that, when accompanied by adequate exploration and testing, the use of soil blankets and preloads on

[1] Mr. Barber is also Associate Professor of Civil Engineering at the University of Maryland, College Park, Md.

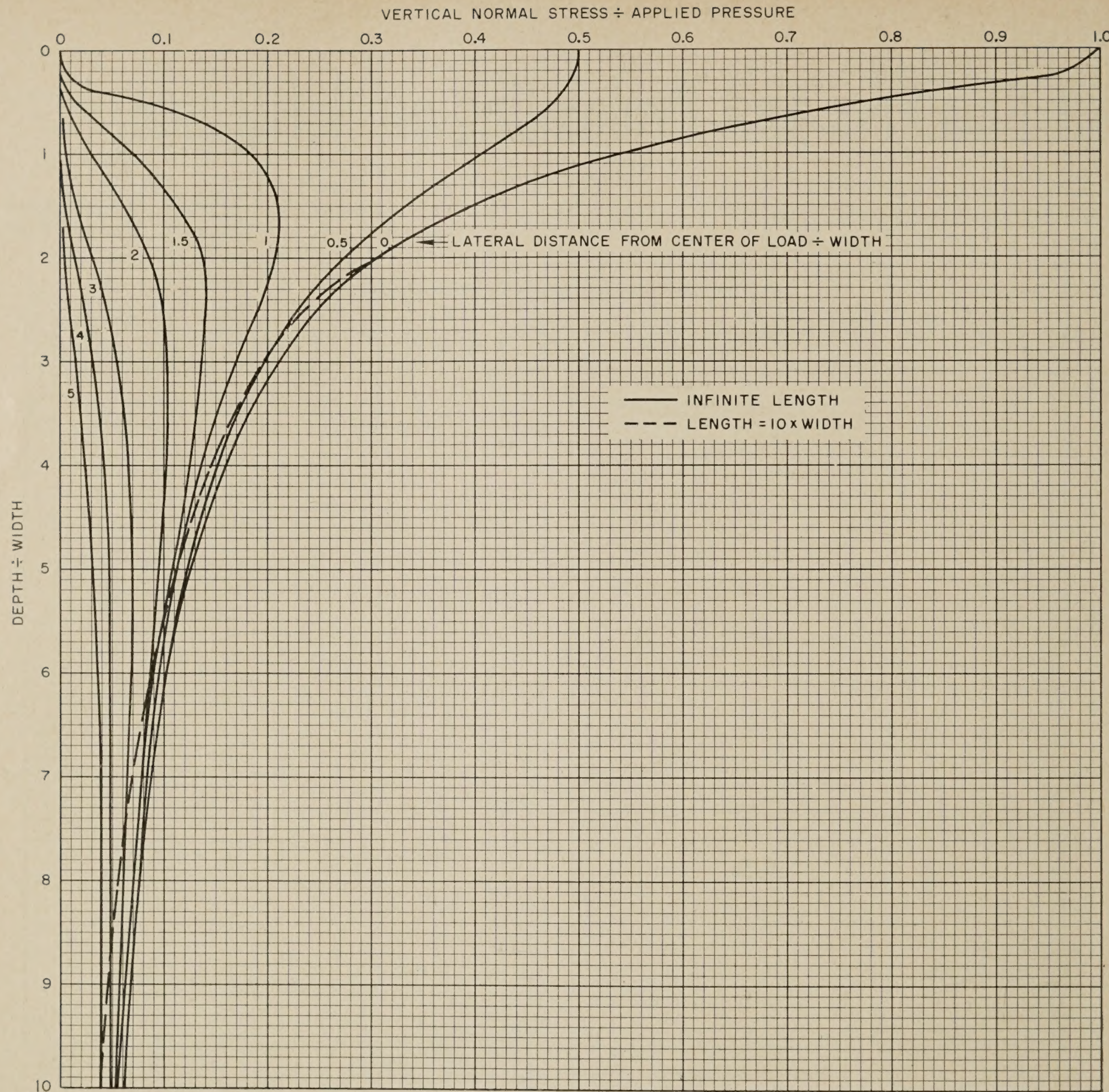


Figure 2.—Vertical normal stress from uniformly loaded rectangle.

compressible soil can sometimes provide a satisfactory foundation. Use of the procedures described herein will often obviate the need for construction of deep foundations below compressible material.

Vertical Stresses

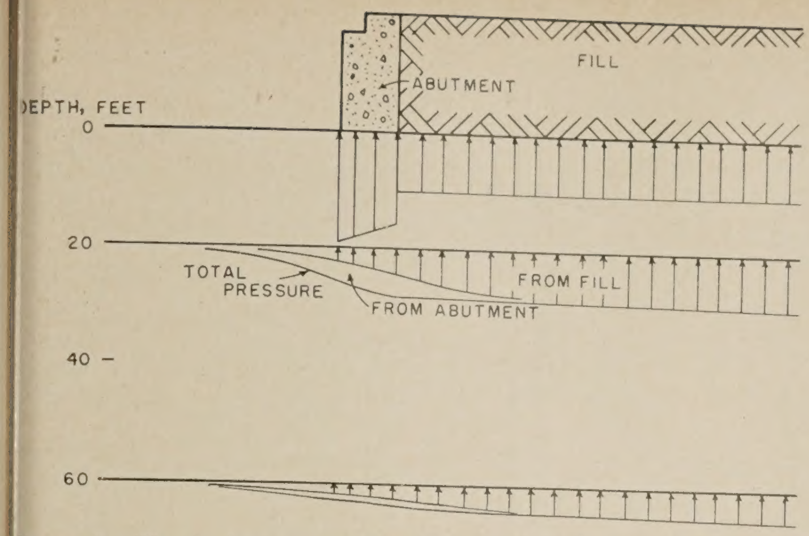
In soils not close to failure, stress distribution is generally calculated on the basis of the theory of elasticity (*1*),[2] which has been shown by test to be applicable to soil (*2*). Based on integration of the Boussinesq formula, the vertical stress produced by a uniform pressure over a square area in a homogeneous elastic medium is shown in figure 1. Also shown is the maximum stress under the center of the load and at different lateral distances. Similar stresses are shown in figure 2 for a uniform strip load of infinite length, and the maximum stress also is shown under a uniformly loaded rectangle whose length is 10 times the width. As depth increases, the total load becomes more important than the applied unit stress; thus, to produce a given stress at given depth, as the loaded area is decreased a higher unit pressure must be applied. For example, consider an inplace, loose, granular blanket 10 feet thick in which it is desired to support strip footings 2 feet wide, 2.5 feet below the surface and loaded to 2 kips per square foot. At the bottom of the blanket, the dep[th] divided by the width is:

$$(10-2.5)\div 2=3.75$$

From data in figure 2, which shows a maxim[um] ratio of vertical normal stress divided by t[he] applied pressure of 0.17 (under the center [of] the footing, curve marked 0), a vertical str[ess] of 0.17×2 equals 0.34 kip per square f[oot] (k.s.f.) at the effective depth of 7.5 feet, c[an] be determined.

To determine the rolling pressure requi[red] at the surface of the blanket to produ[ce] essentially the same stress at the bottom [of] the blanket, use data in figure 1. Here [the] effective depth is 10 feet or the same as [the]

[2] Italic numbers in parentheses indicate the references listed on p. 258.



'igure 3.—*Vertical pressure at different depths in soil from 10-by-30-foot abutm:nt and a fill 20 feet high and an average of 60 feet wide.*

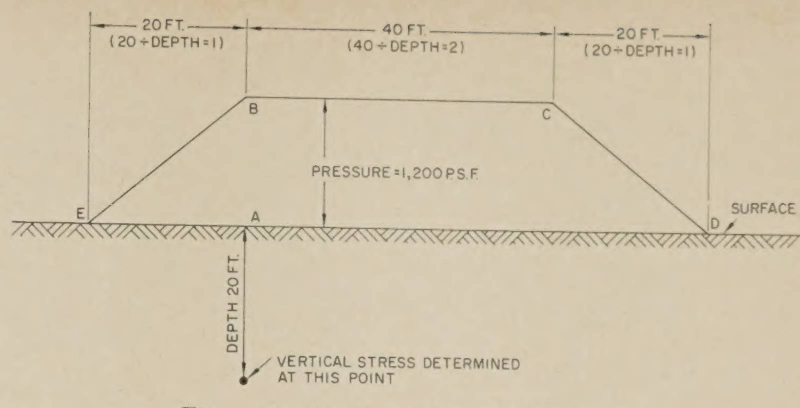


Figure 5.—Cross section of strip load.

ıickness of the blanket. Assume that a 40-›n roller acts on a 4-foot-square area with a ressure of 5 k.s.f. It can be determined by se of data from figure 1 that a pressure at a)-foot depth of 0.07(5) equals 0.35 k.s.f. 'hus, 5 k.s.f. on a small area is required to btain the same pressure 10 feet below the ırface as 2 k.s.f. on a long strip at an effective epth of 7.5 feet. Figure 3 illustrates how the ll behind an abutment is the major contrib-tor of stress at any but shallow depths. or a grade separation, temporary fill across ıe gap between two approach fills may be sed to preload a deep compressible layer to resses equal to those produced by bridge ads.

For determining the preload required for rip loads of nonuniform cross section, the fluence chart, figure 4, was developed. To determine the stress at a given distance below point A (lower left corner), the load cross section is drawn on the chart using lateral distance from A divided by depth as the horizontal scale and any convenient vertical scale for pressure. The stress factor is the sum of influence blocks covered by the cross section, multiplied by the appropriate influence factors. The vertical stress at the specified depth is then the product of the pressure, corresponding to unit pressure on the chart, and the stress factor.

For example, consider the long strip load shown in figure 5. For stress at a depth of 20 feet the lateral distances are divided by 20 feet to obtain lateral distance ratios of 1 from E to B, 2 from B to C, and 1 from C to D. Using these ratios and arbitrarily plotting the maximum pressure at half the height of the chart in figure 4, points B, C, and D are located with respect to A. E would be to the left of A, but since the chart, if extended, would be symmetrical about A, E is plotted to the right as though the loading diagram were folded about AB. The number of influence blocks used to determine a total stress factor of 0.369 was:

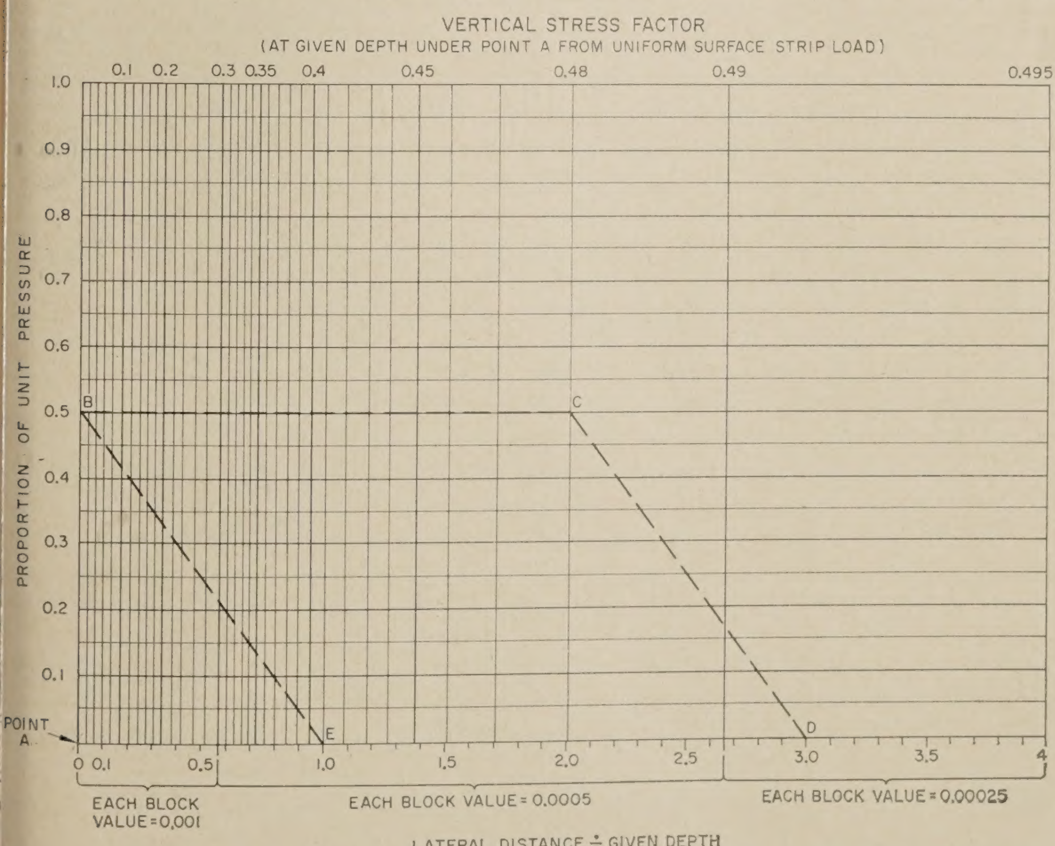
Block				Stress factor
Value	*Number* **ABCD**	*Number* **ABE**	*Total*	
0.001	150	112	262	0.262
0.0005	188	26	214	0.107

Fractional values of blocks were used in balancing deficiencies in the 0.0005 blocks. The pressure corresponding to unit pressure is

$$(1 \div 0.5)1{,}200 = 2{,}400 \text{ p.s.f.}$$

The vertical stress 20 feet below point A shown in figure 5 then would be

$$2{,}400 \times 0.369 = 886 \text{ p.s.f.}$$



'gure 4.—*Chart for computing vertical stress at any point from surface strip load, stress = pressure × factor.*

Settlement

For consolidation and no lateral displacement, Poisson's ratio equal to zero is used. For this condition, settlement is proportional to the area between the vertical stress curve and the axis of depth, as determined from use of information in figures 1 or 2. Settlement factors based on integration of the areas between stress curves and depth axes are shown in figure 6 for different rectangles loaded uniformly. The effect of a moment is also shown in figure 6. For example, consider a rectangle uniformly loaded to 4 kips per square foot (inset in fig. 6) where B=20 feet and L=40 feet. The settlement is to be determined under the point A that is caused by compression of a layer between 10 and 20 feet deep (points C and A) for which the strain per unit pressure, m_v, is 1 percent per kip per square foot. In figure 6, for

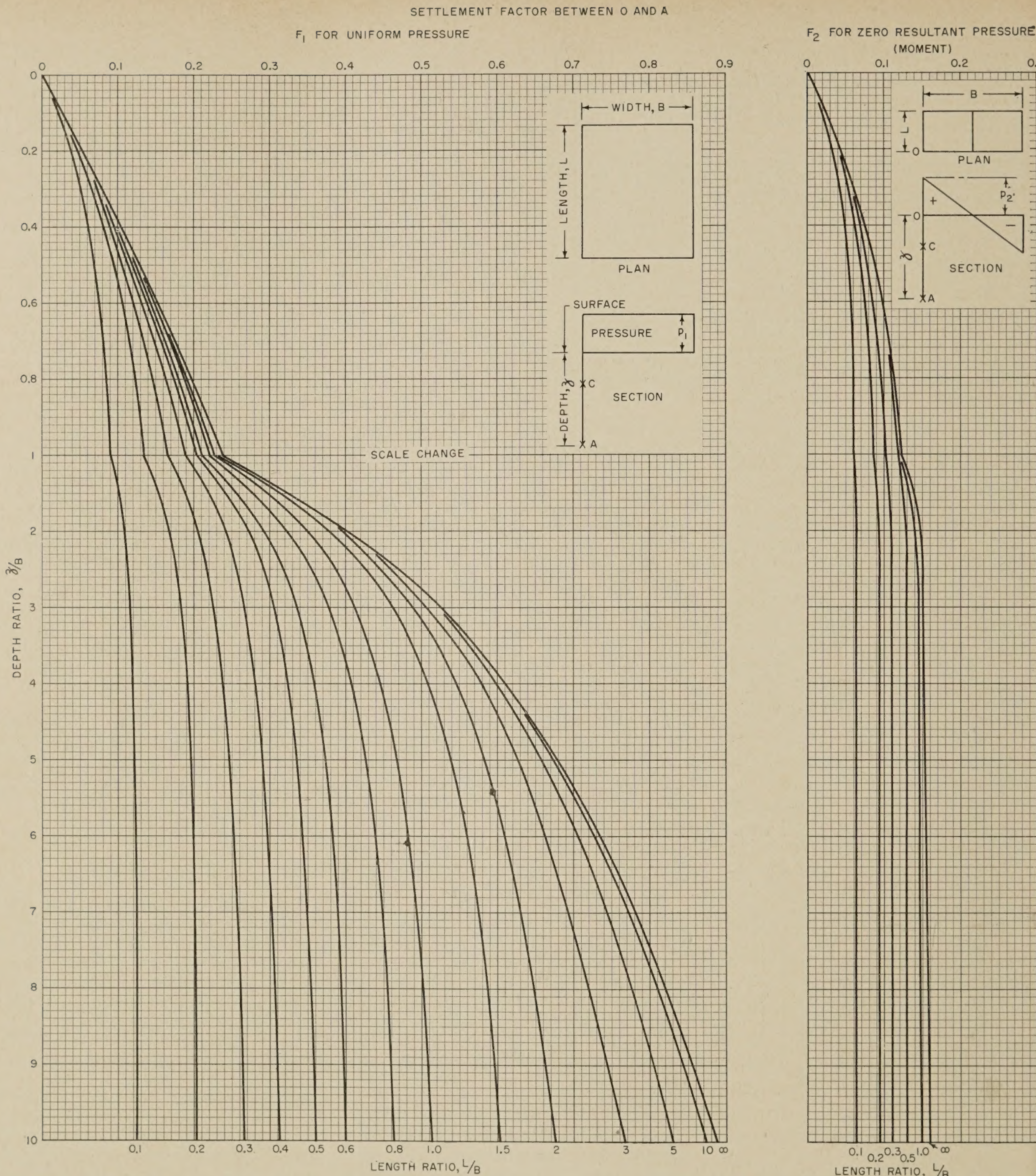
$$L \div B = 40 \div 20 = 2,$$

read F_1 values of 0.13 and 0.24 respectively for

$$z \div B = 10 \div 20 = 0.5 \text{ and } 20 \div 20 = 1.$$

Using the equation at the bottom of figure 6, the settlement is

$$0.01 \times 4 \times 20 \times (0.24 - 0.13) = 0.088 \text{ feet.}$$



SETTLEMENT, $S = m_v pBF$. m_v = STRAIN PER UNIT PRESSURE INCREASE FROM CONSOLIDATION TEST CORRESPONDING TO AVERAGE PRESSURE, $\frac{pF}{z/B}$. VERTICAL PRESSURE AT A POINT IS p X SLOPE OF CURVE = $p\frac{dF}{d(z/B)}$. FOR LAYER BETWEEN C AND A, USE $F = F_A - F_C$. FOR A POINT NOT BELOW CORNER, USE COMBINED AREAS THUS: FOR [I | B_I III / II | B_{II} IV], USE $BF = B_I(F_I + F_{III}) + B_{II}(F_{II} + F_{IV})$. FOR TRAPEZOIDAL PRESSURE DISTRIBUTION, USE AVERAGE PRESSURE, p, AND COMBINE F_1 AND F_2, THUS: FOR [p_2, p_1, B] USE $F = F_1 + \frac{p_2}{p_1} F_2$ AND $p = p_1$; FOR [$L/B \geq 2$, a, p_3, p_1, B], $F = F_1 + \frac{a}{B} F_2$ AND $p = p_1 = p_3(1 - a/2B)$.

Figure 6.—Graph of settlement under corner of load on rectangular area, Poisson's ratio = 0.

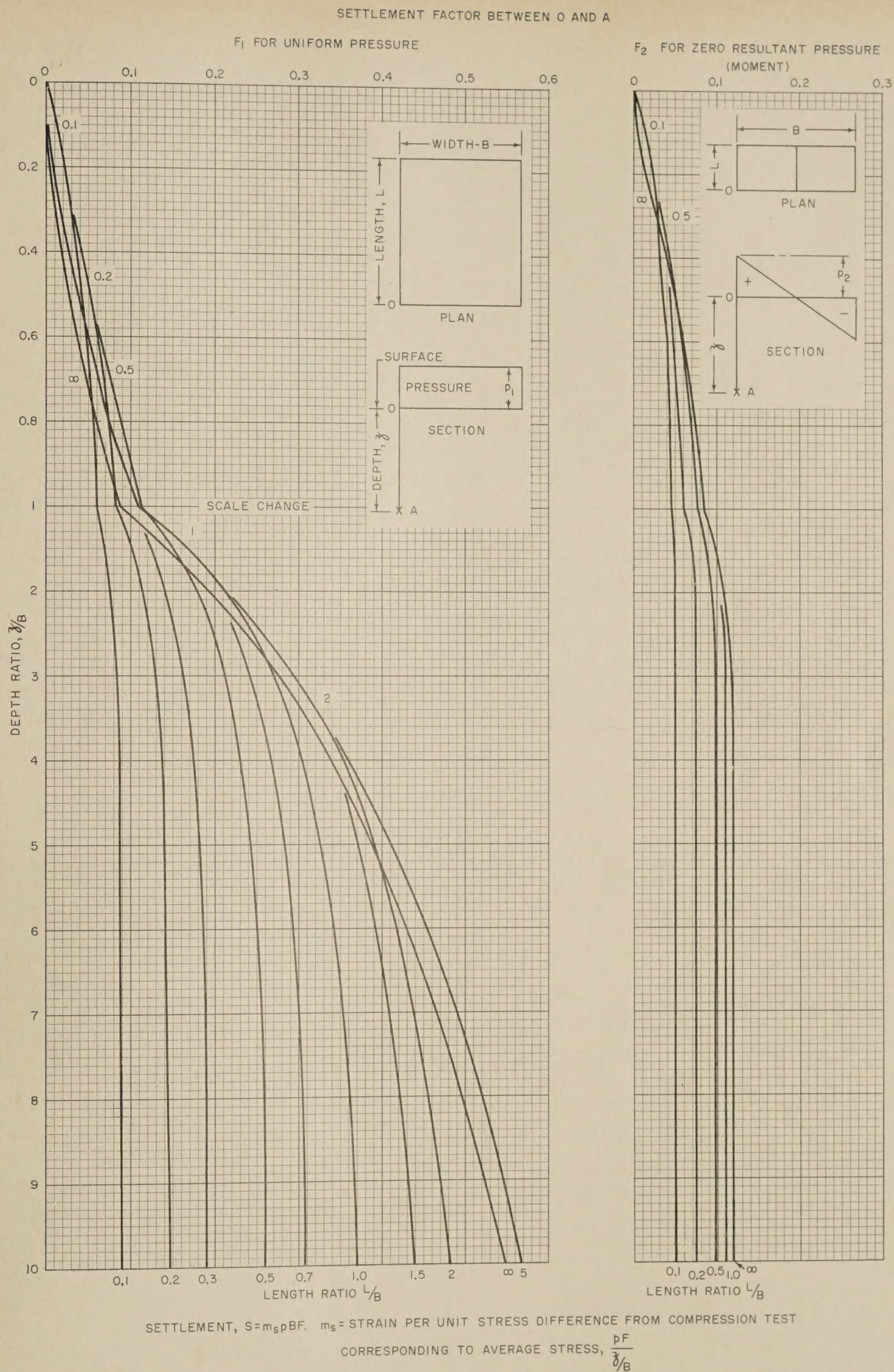


Figure 7.—Graph of settlement under corner of load on rectangular area, Poisson's ratio=0.5.

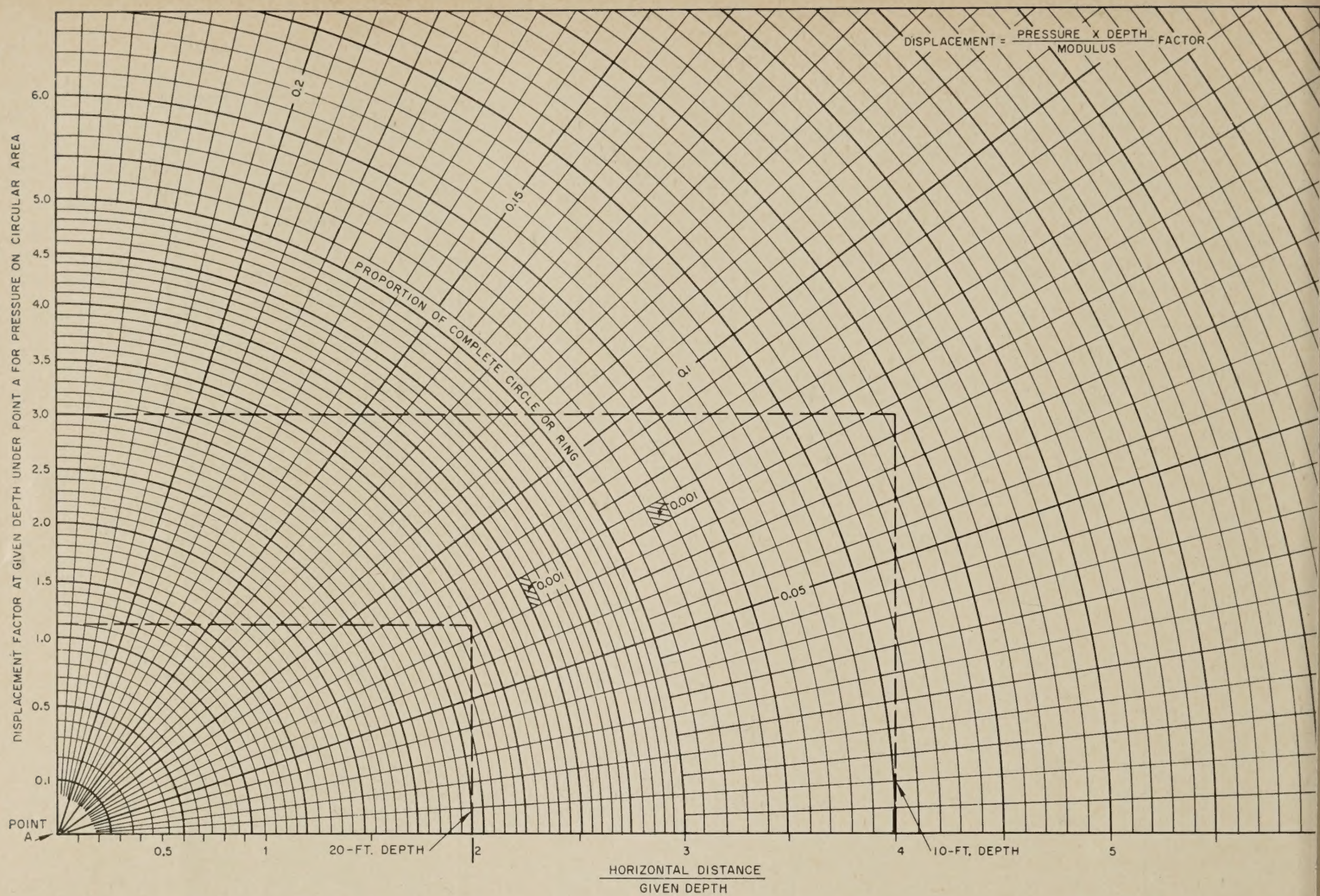


Figure 8.—Chart for computing vertical displacement below the surface from finite surface load, Poisson's ratio=0.

For Poisson's ratio equals 0.5, corresponding to shear at constant volume, settlement factors are a function of both vertical and lateral normal stresses. Integration for this condition produced data for figure 7, which shows settlement factors under different loaded rectangular areas for Poisson's ratio equals 0.5.

Settlement factors for other shapes may be obtained from influence charts such as figure 8, which is similar to Newmark's chart for vertical stress (*3*). For a displacement factor for material below a given depth under point **A** (lower left corner), the loaded area is located to scale and the number of blocks covered by the area is multiplied by 0.001 (influence value per block) to obtain the factor. The displacement is calculated by this factor multiplied by applied pressure multiplied by the depth that is then divided by modulus of elasticity between the surface and the given depth.

$$\text{Displacement} = p \times \mathcal{Z} \times \mathbf{F} \div \text{modulus}.$$

Although, figure 8 information can be used for calculating settlement factor for more irregular areas; its use is illustrated by solving the problem used to illustrate figure 6.

The rectangular loaded area is plotted in figure 8 to the appropriate scale for each depth. To prevent error that possibly might be caused by nonuniform shrinkage of the paper on which figure 8 is printed, both the width÷depth and the length÷depth ratios are plotted on the bottom scale and the width÷depth ratios transferred to the vertical scale by following the appropriate curves, whi were originally arcs. The number of bloc covered are 1,270 and 525, respectively, f the rectangles for 10-foot depth and t

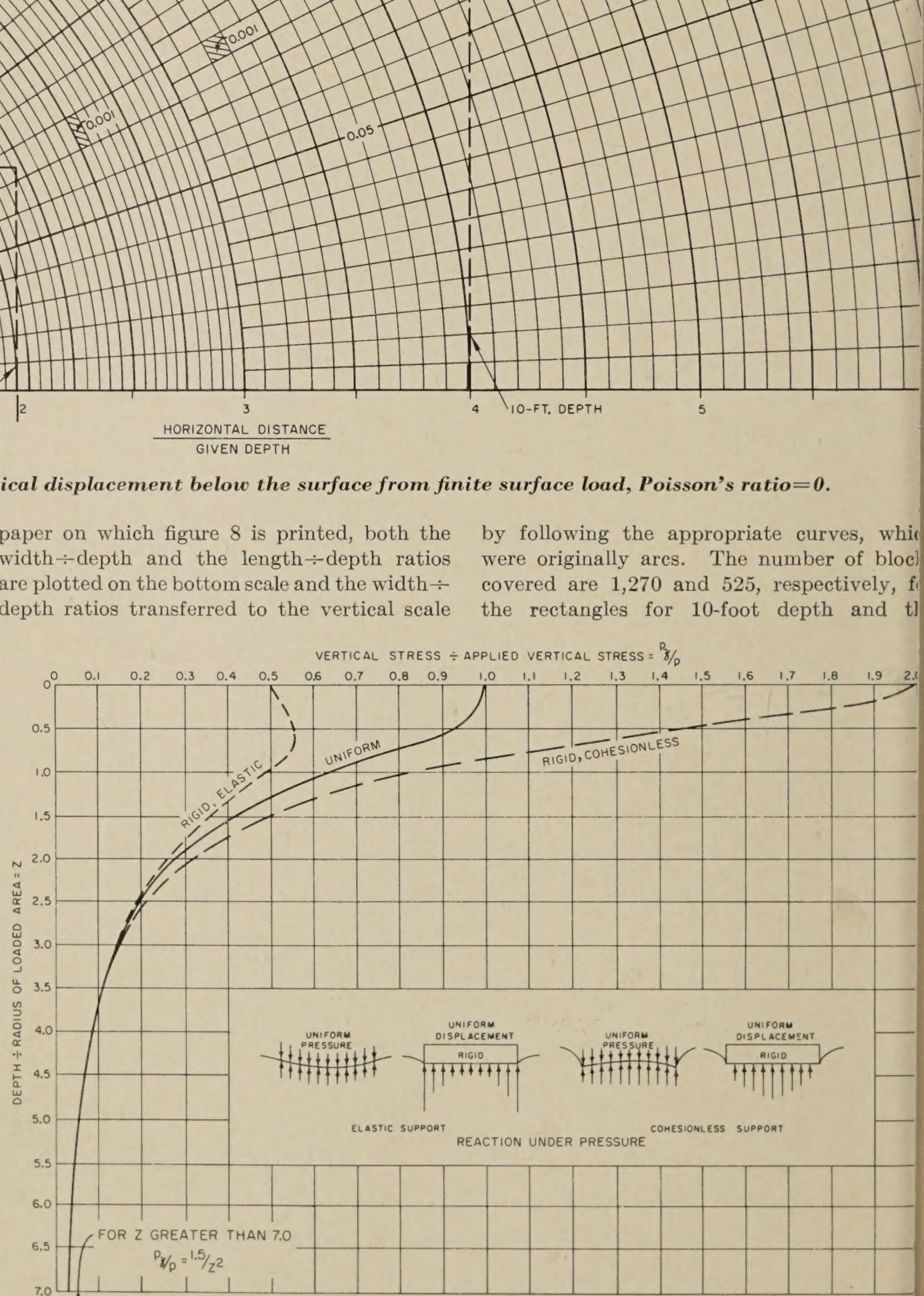


Figure 9.—Vertical stresses on axis below vertical stress over circular area at surface

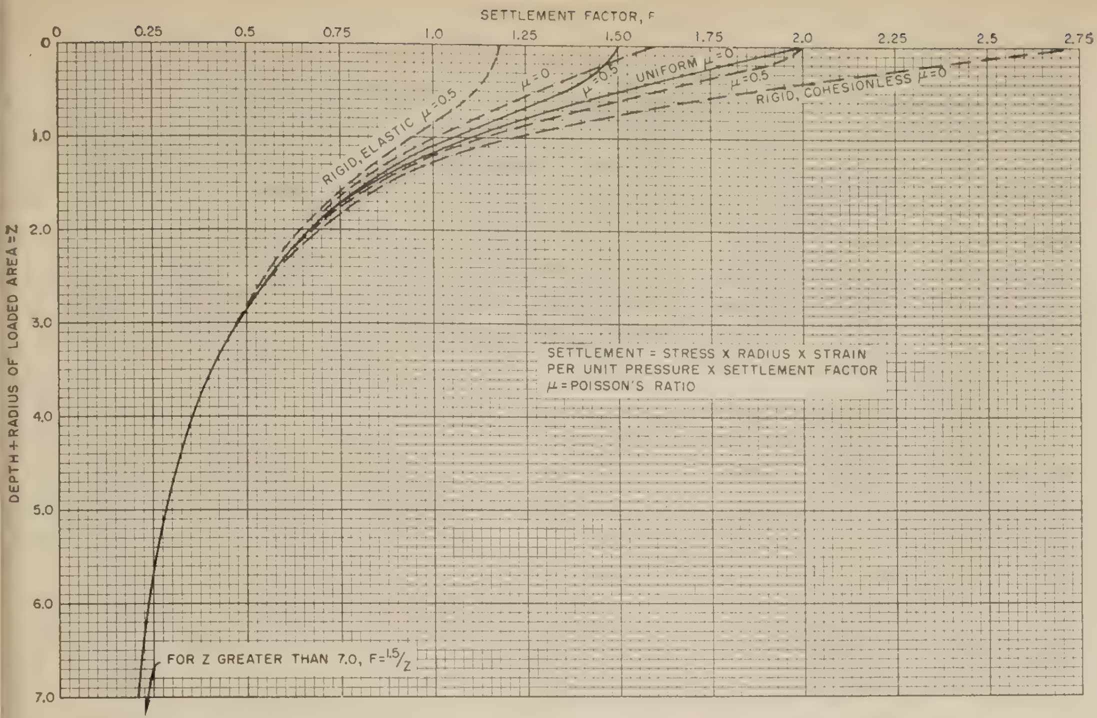


Figure 10.—Settlement factors on axis below vertical stress over circular area at surface.

20-foot depth. The net product, depth times factor, is then

$$0.001(10\times 1{,}270-20\times 525)=2.2.$$

As the strain per unit pressure is the reciprocal of the modulus, the displacement is

$$0.01\times 4\times 2.2=0.088 \text{ foot.}$$

In figures 1, 2, 6, and 7 a uniform stress has been assumed. A rigid footing concentrates stress at the edges unless the materials there cannot carry the stress. For footings on sand at a shallow depth, the stress is concentrated near the center (parabolic distribution). The effects of these differences on stress and settlement decrease with depth for load on a circular area (*4*), as illustrated in figures 9 and 10.

Effects of Blankets and Preloading

Figure 11 shows the vertical pressure in a homogeneous material under a typical footing, 6 feet square, uniformly loaded to 3 k.s.f. Depth zero is at the bottom of the footing, which may be below the surface; the effect of depth of footing on stress distribution is neglected. Excavation over only the footing area is subtracted from the total footing pressure to obtain the net footing pressure, 3 k.s.f., as illustrated. Consider three layers in the soil foundation having compressibilities of: m_1 for 0 to 6 feet, m_2 for 6 to 18 feet, and m_3 below 18 feet. The compressibility is strain divided by stress for the appropriate range of stress; it is the reciprocal of the modulus of elasticity. A small m corresponds to low compressibility (a high modulus of elasticity).

If m_1 is smaller than m_2, the stresses in the second layer would actually be less than shown in figure 11. The stress distributing ability is roughly proportional to the cube root of $1\div m$ (*5*). Conversely, if m_3 is very small compared to m_2, the stresses will be higher; over a rigid base, the vertical stress at any depth is increased to approximately that at three-fourths the vertical stress at the same depth in a homogeneous material. For simplicity, these effects are not considered in this article.

If the upper layer is a blanket having a very small m_1, the settlement is proportional to m_2 times the area to the left of the stress curve between 6 and 18 feet, plus m_3 times the area below 18 feet. If, over a large area, an excavation equivalent to 150 p.s.f. (0.15) k.s.f. has been made, the area to the left of this stress only produces settlement proportional to the reloading compressibility, which is usually much less than the compressibility for the first application of a load. The principal settlement would be proportional to the area in figure 11 between the vertical line at 0.15 k.s.f. and the stress curve between 6 and 18 feet, as the compressibility above 6 feet was assumed to be small and the material below 18 feet is being reloaded. Using the stress curves for zero lateral distance in figures 1 and 2 and the geometry described, settlement factors for different preloadings were calculated.

The reduction of settlement factors with preloading (assuming 100 percent consolidation with respect to time) for a loaded square area is shown in figure 12 and for a loaded rectangular area, the length of which is equal to 10 times the width, in figure 13. Reading from figure 12, the settlement factor for a uniformly loaded square area on a homogeneous foundation (no preload) is 1.12 at zero depth. For negligible compressibility such as a compacted granular blanket in the top 6 feet under a 6- by 6-foot-square loaded area (fig. 11), the settlement factor is reduced to 0.42 (depth divided by width=6 divided by 6=1). For a preload of 0.15 k.s.f., and a footing pressure of 3 k.s.f., preload divided by applied pressure=0.15 divided by 3=0.05, and the settlement factor below 6 feet, from figure 12, is 0.17. For this preload, the settlement factor is zero below a depth divided

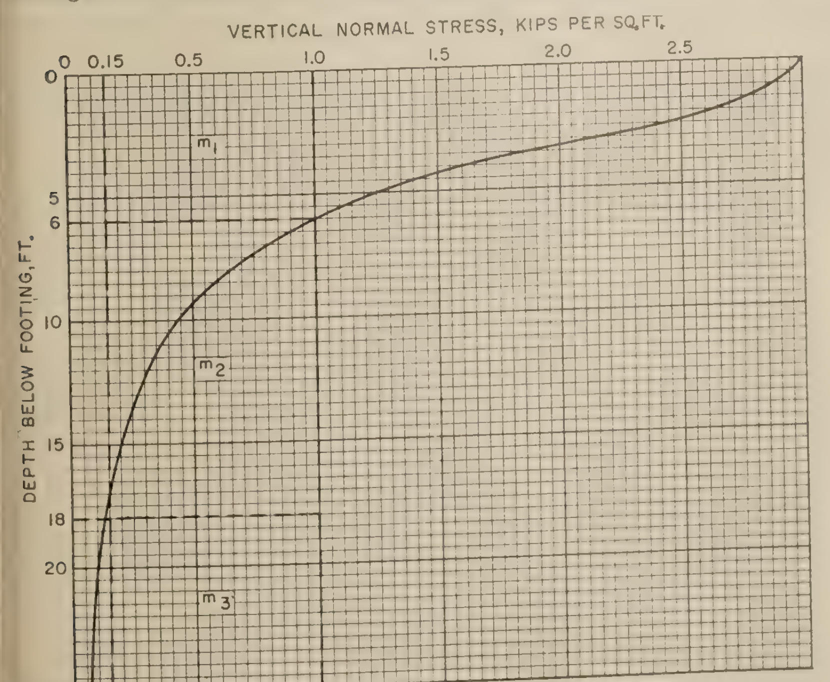


Figure 11.—Stress versus depth under pressure of 3 kips per square foot on a 6-by-6-foot-square footing.

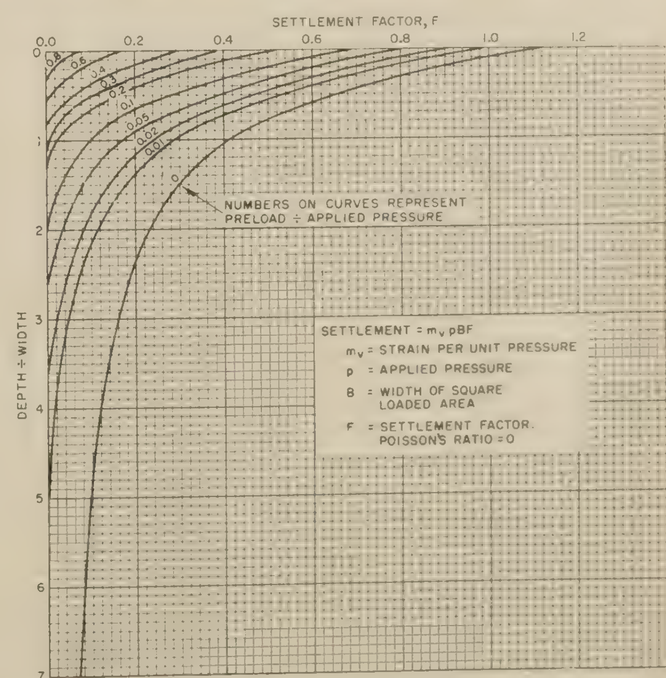


Figure 12.—Maximum settlement under uniformly loaded square of different preloads.

by width=3, which corresponds to a depth of $3 \times 6 = 18$ feet.

To calculate the stress for no settlement (except recompression) below 6 feet, figure 12 data can be used. For depth divided by width=1, preloading of 0.33 multiplied by the applied pressure equals the stress. For the applied load of 3 k.s.f., the preloading is 1 k.s.f. or stress at the depth of 6 feet. The stress could also be determined by use of figure 1, where vertical normal stress divided by applied pressure is 0.33 when depth divided by width=1.

Preconsolidation Factors

Because of the imperfect elasticity of soil, the second application of a stress produces less strain than the first application. The maximum previous stress is termed the preconsolidation pressure. The preconsolidation pressure may be determined from loading history, including water pressure, and may be inferred from the shape of the stress-strain curve in consolidation. The shape of the stress-void ratio curve gives the same result but requires unnecessary arithmetic for calculating void ratio from measured strain. The strain-log stress curve for a sediment is often fairly linear for loads heavier than the preconsolidation pressure.

Care must be taken during sampling and testing to assure that samples are sufficiently undisturbed and that variation in the stress-strain relationship actually is the result of preconsolidation. Figure 14 shows the strain-stress log curve for a residual soil derived from schist. At first glance, it has a preconsolidation pressure between 1 and 2 k.s.f. However, this is simply a function of the plotting scales as shown by the arithmetic plot in figure 15, which reflects a perfectly linear relation between stress and strain.

For some soils, such as mudflows and loess, the strain may be markedly increased by submergence under water.

Compacting the soil by rolling in layers produces an effect similar to preconsolidation. For fine-grained soils, such preconsolidation is about 2 to 4 k.s.f. at 100 percent of maximum density and 1 to 2 k.s.f. at 95 percent of maximum density as determined by AASHO Designation: T 99. The effective preconsolidation is higher for granular materials. The compressibility varies with moisture as well as with density and should be determined for each situation for the range of anticipated conditions.

Time Requirements

If preconsolidation is to be obtained by a temporary preload, the time required for consolidation must be considered. For a deep compressible layer that has drainage at its upper boundary, figure 16 relates the time to consolidation at different depths. Mathematically this is similar to the rate at which a change in surface temperature penetrates the earth (*6*).

For example, use figure 11 and assume that it is desired to preconsolidate the soil at a depth of 18 feet by an additional 0.15 k.s.f., the stress that is to be transmitted from the proposed footing. Assume a temporary preload of 1 k.s.f. over a large area and drainage at and above the 6-foot depth. The time for consolidation or load transfer equivalent to 0.15 k.s.f. at the 18-foot depth may be determined from figure 16. Degree of consolidation may be considered as settlement at a given time divided by final settlement or it may be considered as effective stress increase at a given time divided by the final effective stress increase; that is, when the excess pore pressure from the applied load is zero. The second definition, based on load transfer to the soil skelton, is used herein.

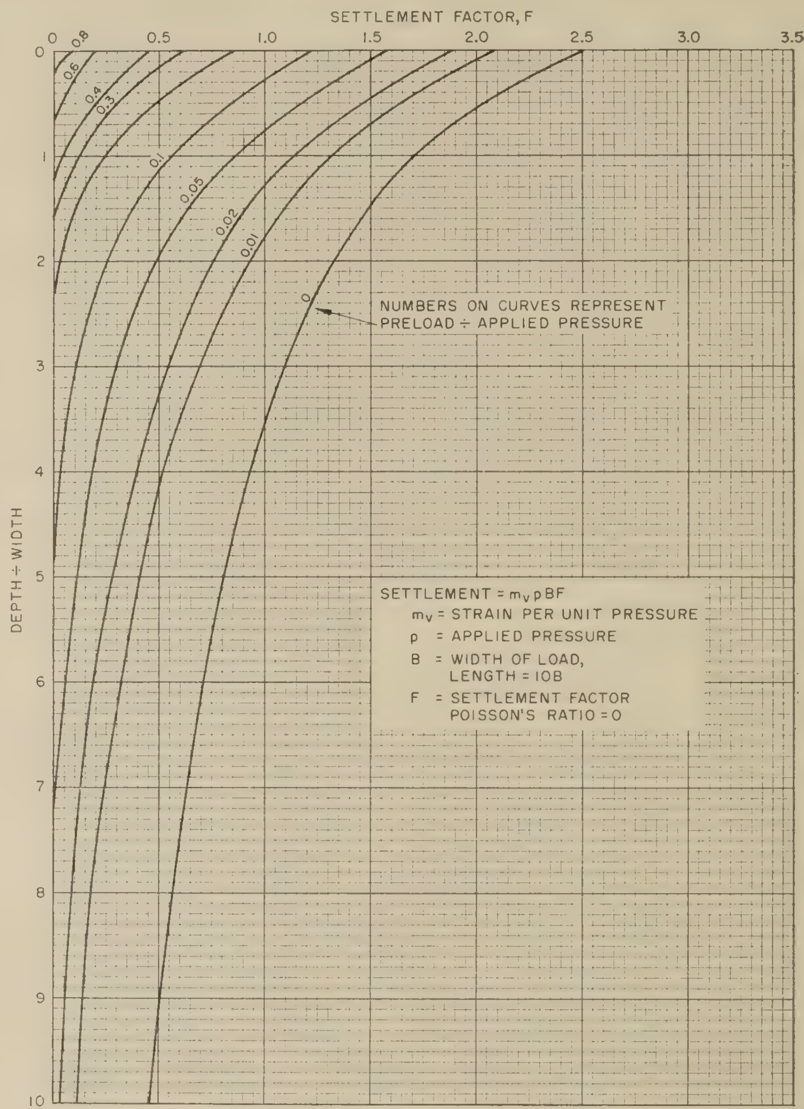


Figure 13.—Maximum settlement under normally loaded rectangle of different preloads.

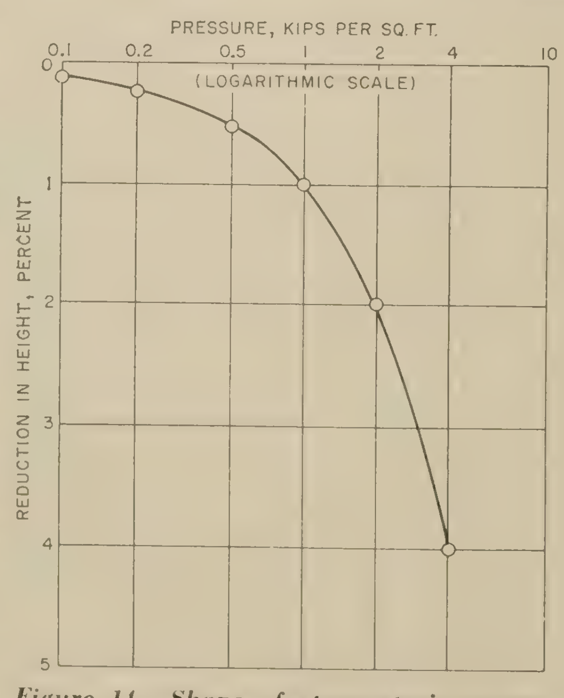


Figure 14.—Shape of stress-strain curves, logarithmic scale.

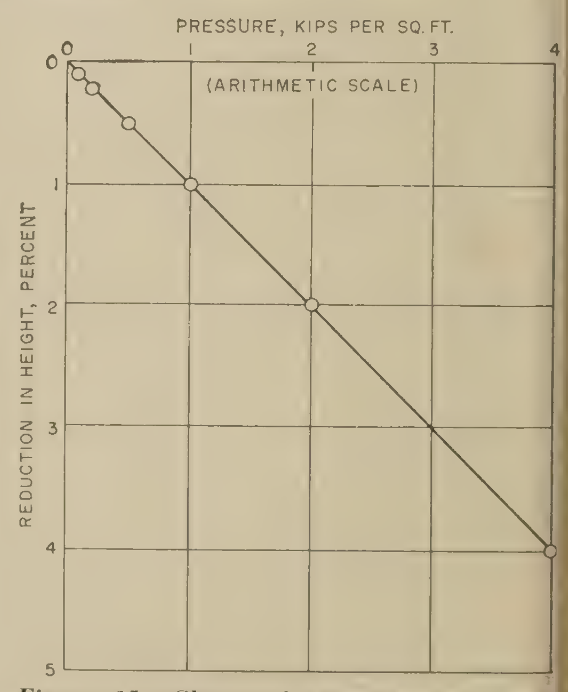


Figure 15.—Shape of stress-strain curves, arithmetic scale.

The depth from drainage surface is

$$18-6=12 \text{ feet} = \mathbf{H}.$$

The required degree of consolidation is 0.15 k.s.f. divided by 1 k.s.f. = 0.15. For these coordinates (0.15, **H**), figure 16 gives a relative time of

$$T = tc_v \div \mathbf{H}^2 = 0.24.$$

The actual time, t, depends on the coefficient of consolidation, c_v, of the soil, which may be determined from laboratory time-consolidation tests on undisturbed samples (7). The time is

$$T\mathbf{H}^2 \div c_v = 0.24 \times 12^2 \div c_v = 34 \div c_v$$

If c_v were 0.1 foot squared per day, the time would be 340 days. A comparison of the curves in figures 16 and 11 shows that degree of consolidation decreases more rapidly with depth than does stress. Because of this, with respect to footing stress the soil between depths of 6 feet and 18 feet will be overconsolidated and below 18 feet will be underconsolidated. Much more time would be required to fully preconsolidate the soil below the 18-foot depth.

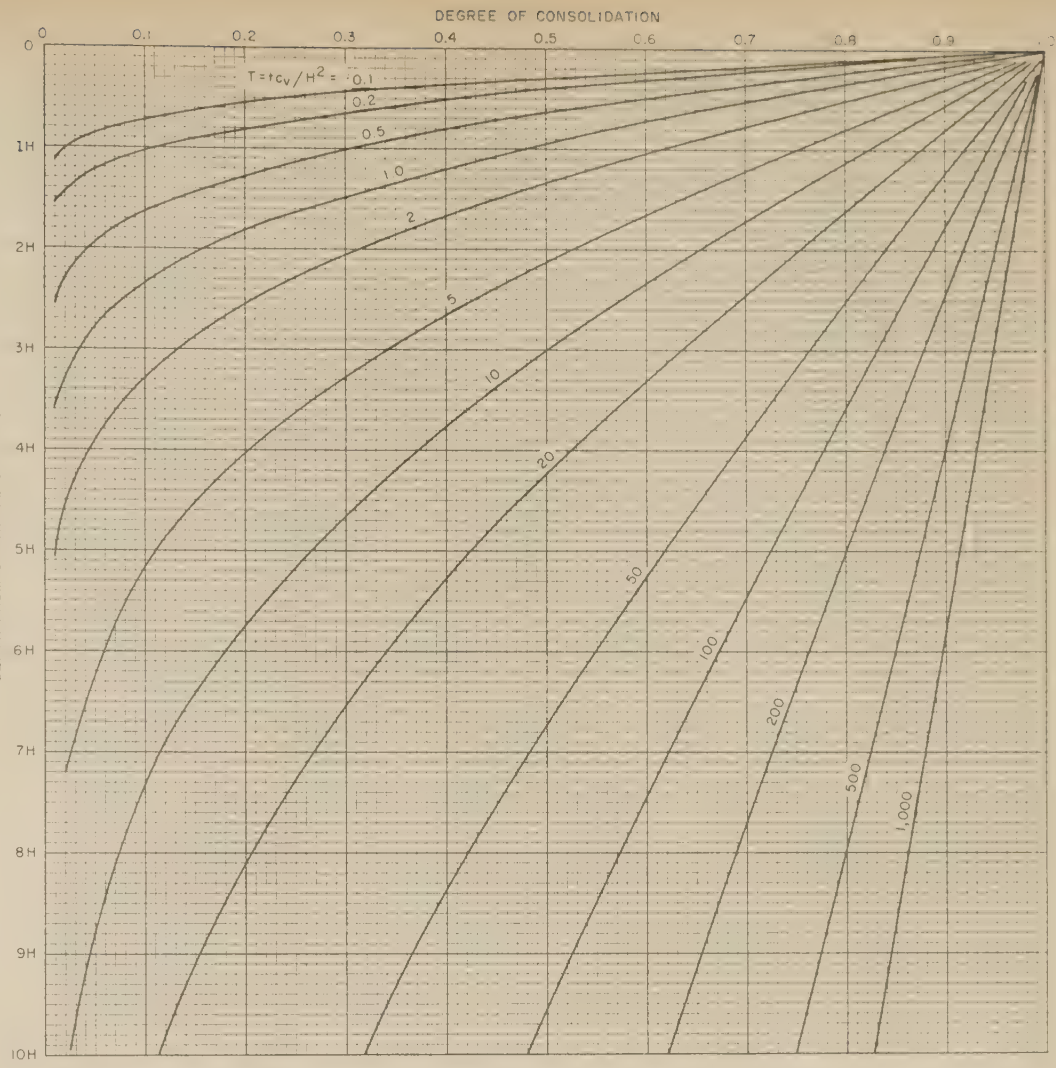


Figure 16.—Time-consolidation below surface of semi-infinite mass.

Preload Duration

It is sometimes considered that 100-percent consolidation can be obtained by using a balanced combination of preload and preload duration. For example, a preload equal to twice the design load and a time sufficient to obtain 50-percent consolidation under the preload would be a balanced combination. Such a combination would satisfactorily prevent additional consolidation under the design load, if the preloading consolidated all points within the compressible layer to at least 50 percent of the preload stress. But care must be taken in using average consolidation to determine preload duration; some points will be overconsolidated and others underconsolidated in relation to design load stresses. For example, by using table 1 data, for a layer having two drainage faces, both faces permeable, and an average degree of consolidation of 0.5, the time factor (T) equals 0.05. For this same time factor, table 3 contains an interpolated degree of consolidation for a point at the center of the layer of only 0.23 (between 0.046 and 0.060 opposite center of slab). This point is represented by point **B** in figure 17. Thus from a temporary load twice the final load, the average degree of consolidation would be $0.5 \times 2 = 1$ or 100 percent, but a central point would be consolidated to only (0.23×2) or 0.46 percent of the final load.

The consolidation remaining is represented in figure 17 by the area **ABC**. This area has been evaluated as 20 percent of the total load transfer of the final load. The remaining settlement then would be approximately 20 percent of the settlement under the final load. For example, if settlement under the final load were 1 foot, then a 20-percent increase in load transfer would increase the settlement to 1.2 feet. This would be partly compensated by rebound of the overconsolidated material adjacent to the drainage faces. Table 2 shows the consolidation remaining for different preloads and balanced durations in relation to average consolidation. To obtain complete

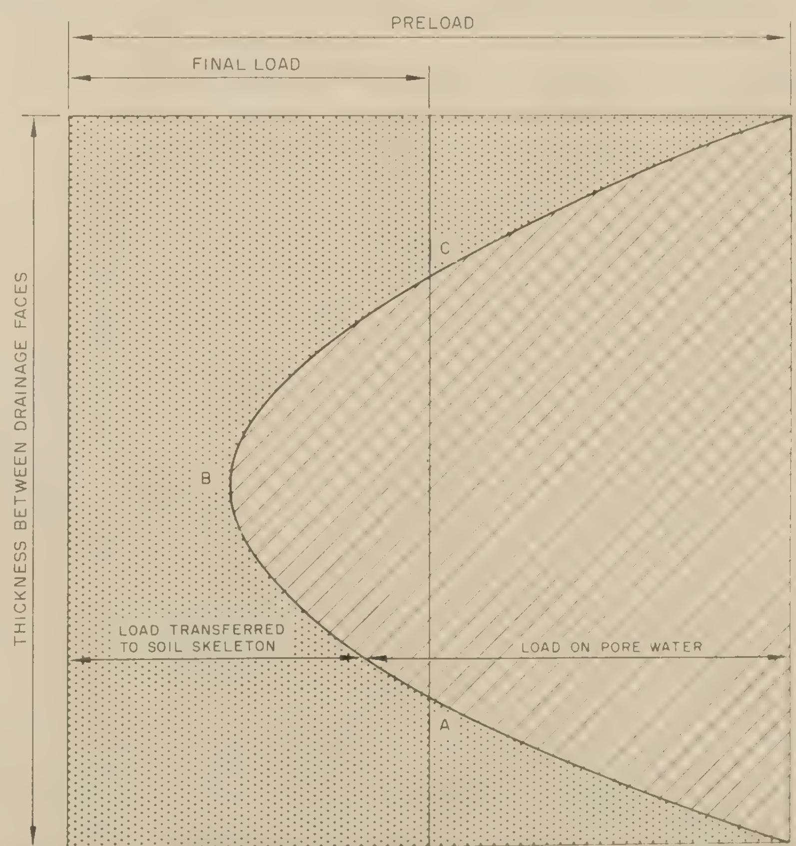


Figure 17.—Load transfer during preloading of layer having two drainage faces.

Table 1.—Average consolidation of uniformly stressed[1] mass

Boundary conditions	Time factor,[2] $T = \frac{c_v t}{H^2}$, for degree of consolidation or load transfer of--										
	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
Slab of thickness H:											
Both faces permeable------------	0.0005	0.002	0.008	0.018	0.031	0.05	0.07	0.10	0.14	0.21	0.28
One face impermeable:											
Ratio (pressure at permeable face to pressure at impermeable face):											
0--------------------------	0.024	0.049	0.100	0.154	0.217	0.29	0.38	0.50	0.66	0.95	1.22
0.2------------------------	0.009	0.027	0.073	0.126	0.186	0.26	0.35	0.46	0.63	0.92	1.19
0.4------------------------	0.005	0.016	0.056	0.106	0.164	0.24	0.33	0.44	0.60	0.90	1.17
0.6------------------------	0.003	0.012	0.042	0.092	0.148	0.22	0.31	0.42	0.58	0.88	1.15
0.8------------------------	0.002	0.010	0.036	0.079	0.134	0.20	0.29	0.41	0.57	0.86	1.14
1.0------------------------	0.002	0.008	0.031	0.071	0.126	0.20	0.29	0.40	0.56	0.85	1.13
1.5------------------------	0.002	0.006	0.024	0.058	0.107	0.17	0.26	0.38	0.54	0.83	1.11
2.0------------------------	0.002	0.005	0.019	0.050	0.095	0.16	0.24	0.36	0.52	0.81	1.10
5.0------------------------	0.001	0.003	0.013	0.034	0.069	0.12	0.20	0.32	0.48	0.77	1.07
10.0-----------------------	0.001	0.003	0.011	0.028	0.060	0.11	0.18	0.30	0.46	0.75	1.05
Infinite-------------------	0.001	0.002	0.009	0.024	0.048	0.09	0.16	0.28	0.44	0.73	1.03
Sphere of diameter H--------------	0.00005	0.0002	0.001	0.002	0.005	0.008	0.012	0.019	0.028	0.046	0.063
Cylinder of diameter H------------	0.0002	0.001	0.002	0.005	0.010	0.016	0.024	0.036	0.053	0.083	0.114
Cylinder of diameter H, having internal drain of diameter d; ratio of:											
0.01---------------------------	0.021	0.046	0.104	0.167	0.24	0.33	0.44	0.58	0.78	1.10	1.45
0.025--------------------------	0.014	0.032	0.075	0.124	0.18	0.25	0.33	0.44	0.58	0.86	1.13
0.1----------------------------	0.005	0.014	0.037	0.064	0.096	0.132	0.178	0.24	0.32	0.46	0.60
0.2----------------------------	0.002	0.006	0.019	0.035	0.054	0.077	0.105	0.14	0.19	0.28	0.37
Steady accumulation on impervious base to depth H, in time t-------	0.05	0.10	0.20	0.31	0.45	0.62	0.90	1.3	2.2	4.3	10
Steady load increase to time t----	0.002	0.005	0.017	0.039	0.071	0.11	0.17	0.26	0.41	0.83	1.67

1/ Unless otherwise noted, load is assumed to be applied instantaneously when time, t, equals zero.

2/ c_v = coefficient of consolidation; t = time; H = distance based on boundary conditions.

consolidation, in the example, the preload would have to be equal to 1 divided by 0.23 or 4.3 times the final load. As an alternate the preload could be left unchanged and the time, *T*, increased to 0.095 (table 3) for 50-percent consolidation.

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(*5*) *Triaxial Compression Test Results Applied to Flexible Pavement Design,* by Edward S. Barber, PUBLIC ROADS, vol. 25, No. 1, September 1947, pp. 1–8.

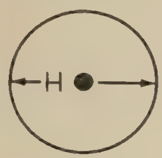
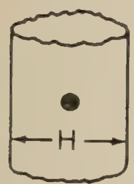
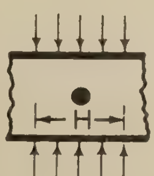
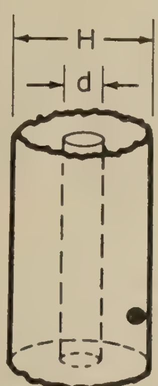
(*6*) *Conduction of Heat in Solids,* by Horatio Scott Carslaw and J. C. Jaeger, Oxford Press, 1947.

(*7*) *Observed Settlements of Highway Struc tures Due to Consolidation of Alluvial Clays* by Edward S. Barber, PUBLIC ROADS, vol. 2(No. 11, December 1951, pp. 217–223.

Table 2.—Consolidation remaining afte temporary preloading

Preload	Balanced consolidation	Average consolidation remaining
Percent of final load	Percent of preload	Percent of final load
110	91	2
120	83	4
150	67	10
200	50	20
300	33	35
400	25	45
500	20	50

Table 3.—Consolidation at a point in a uniformly stressed[1] mass

Boundary conditions[2] and location point		Time factor,[3] $T = \frac{c_v t}{H^2}$, for degree of consolidation or load transfer of--										
		0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
	Center of sphere---	0.014	0.016	0.021	0.025	0.030	0.035	0.040	0.048	0.058	0.076	0.094
	Center of cylinder-	0.017	0.021	0.028	0.035	0.042	0.050	0.060	0.073	0.090	0.120	0.150
	Center of slab-----	0.025	0.033	0.046	0.060	0.076	0.095	0.117	0.146	0.187	0.256	0.328
	Impervious edge of slab--------------	0.100	0.130	0.185	0.241	0.305	0.379	0.467	0.585	0.747	1.022	1.312
	Below surface of semiinfinite mass-	0.130	0.185	0.304	0.465	0.705	1.10	1.82	3.37	7.79	31.7	127
	Center of slab with impervious boundaries--------	0.033	0.046	0.076	0.116	0.176	0.274	0.455	0.842	1.95	7.79	31.7
	Impervious edge of hollow cylinder d/h =											
	0.01-------------	0.050	0.076	0.132	0.20	0.27	0.36	0.47	0.61	0.81	1.13	1.48
	0.025------------	0.041	0.062	0.106	0.156	0.21	0.28	0.36	0.47	0.61	0.89	1.25
	0.1--------------	0.029	0.040	0.066	0.093	0.13	0.16	0.21	0.27	0.35	0.49	0.63
	0.2--------------	0.021	0.029	0.045	0.061	0.08	0.10	0.13	0.17	0.22	0.31	0.40

1/ Stress assumed to be applied instantaneously when time, t, equals zero.

2/ Boundaries are pervious unless noted by heavy line.

3/ c_v = coefficient of consolidation; t = time; H = distance based on boundary conditions.

An Interpretive Review

Mechanisms of Soil-Lime Stabilization

OFFICE OF RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

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The authors of this article present information contradicting some of the hypotheses generally held concerning the mechanisms of the physico-chemical and chemical reactions occurring when lime is added for stabilization of clay soils. The importance of cation exchange, flocculation, and carbonation in the stabilizing process is discounted. Although no test data are included, a summary of results of recent work by the authors is applied to the evaluation of literature available on the mechanisms of the reactions responsible for soil-lime stabilization.

The authors distinguish between rapid ameliorative effects and long-term cementitious reactions in the stabilization process. They postulate that in soil-lime-water mixtures lime is quickly adsorbed by clay mineral surfaces; the ameliorative effects are the result of a very rapid reaction at the edge-to-face points of contact of clay particles within flocs. The reaction is believed to occur between the adsorbed lime on the face surfaces and the alumina and silica groups on the edge surfaces. The reaction involves the production of very small amounts of cementitious compounds such as calcium and aluminum silicate hydrates—which strengthen the contact points in the floc structure sufficiently to improve plasticity and reduce volume change—but not enough to produce the greater strength required for adequately stabilized soil material. The long-term reactions involve the slow and continued formation of further amounts of calcium and aluminum silicate hydrates in the void spaces within and between the flocs. The available literature suggests that a through-solution mechanism is responsible for the long-term reactions, but evidence of the physical adsorption of lime on clay surfaces suggests a surface chemical reaction that is not dependent on prior dissolution of silica and alumina from the clay.

Introduction

STABILIZING soil by the addition of quicklime or hydrated lime is an ancient art that was successfully adapted by engineers of the Texas Highway Department and is now being extensively practiced. The purpose of the authors in writing this article was to attempt to critically evaluate current knowledge of the mechanism or mechanisms responsible for the soil stabilization process, not to discuss the history or the current engineering aspects of soil-lime stabilization. A better understanding of the mechanisms should make it possible to further the development of practical stabilization procedures so that better advantage can be obtained from the use of lime.

The reactions of soil upon treatment with lime are complex, and physical changes in the soil often are dramatic. It has been widely proposed that these unusual changes are the result of: (1) Cation exchange, that is, replacement of the exchangeable sodium, magnesium, or other cation previously held by the soil clay by calcium cations derived from the lime; (2) flocculation of the clay, and consequent increase in effective grain size; (3) carbonation, that is, reaction of the lime with carbon dioxide from the atmosphere to form calcium carbonate, which has been said to exert cementing action; and (4) so-called *pozzolanic reactions* with soil constituents to generate new minerals of a cementitious nature. As explained in detail the authors believe that these four phenomena, although all may occur in a given soil-lime mixture, do not adequately account for the effects observed.

The factor of cation exchange has been mentioned by many authors, yet familiarity with the cation exchange properties of soils should have eliminated this as a serious explanation for the stabilizing effects of lime on soil. Soil scientists know that many natural soils are almost calcium saturated. For example, results of recent research show that the montmorillonitic soils of the southwestern United States (classed as *Grumusols* in soil science classification systems) are normally two-thirds to three-quarters calcium saturated (*1*).[3] Despite this predominance of calcium in the exchange complex, these soils exhibit all the classic deficiencies associated with montmorillonitic soils and, when they are used as subgrades, require stabilization treatment. Although it might be thought that complete calcium saturation is required for stabilization, research results with sodium-saturated soils have demonstrated that when lime is added to a dilute clay suspension in a quantity in excess of that required for saturation a complete exchange of calcium for sodium does not take place (*2*)—not even when conditions are favorable for cation movement. Exchange in comparatively dry compacted soils is undoubtedly less complete.

The concept that flocculation plays a major part in soil-lime stabilization is often voiced, but careful examination of previously known facts shows this also to be an inadequate explanation for the stabilization. Some soils, including most of the red and yellow soils of the southeastern part of the United States, are naturally flocculated; this can be seen by shaking the soil in water and examining the resultant suspension. Despite this natural flocculation these soils are not stable, and they do respond to lime treatment. Furthermore, it is well known that many chemical agents, including different salts, alcohols, acids, ketones, cause immediate flocculation when mixed with clays, but they are valueless for stabilization. The fact that flocculation of clay occurs as a consequence of the addition of lime is a well-known phenomenon, but the achievement of flocculation is clearly not the mechanism by which lime stabilizes soils.

The hypothesis that soil-lime stabilization depends on the carbonation of the lime to form calcium carbonate can be dismissed by reference to the reports of many studies. In these studies reaction of the lime with atmospheric carbon dioxide was precluded by sealing the samples, and the characteristic modification of properties and development of strength associated with lime stabilization were observed. As demonstrated by Eades, Nichols and Grim (*3*), carbonation does take place in the field; but the gain in strength said to accrue from cementation of soil grains by calcium carbonate has not been conclusively demonstrated. The writers believe that the long-term reaction of uncarbonated lime with the soil itself would far outweigh any such contribution, and carbonation is probably a deleterious rather than a helpful phenomenon in soil stabilization.

Following the rejection of these inadequate hypotheses, other more nearly adequate but still incomplete explanations of the mechanisms of lime-soil interaction were considered. Experience indicates that at least two distinct stages of reaction are involved: (1) the immediate or rapid processes that ameliorate t

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[2] The authors acknowledge the contributions made by Dr. W. C. Ormsby, National Bureau of Standards, and Donald G. Fohs, Bureau of Public Roads, in discussions of the literature of soil-lime stabilization.

[3] References indicated by italic numbers in parentheses are listed on pp. 265 and 273.

water-sensitive properties of untreated clay soil, and (2) the slower, long-term reactions that cause formation of the final cementitious products that are indicated by the gradual development of strength in compacted soil-lime mixtures. These two stages of reaction are discussed separately.

Summary

Among physico-chemical mechanisms commonly suggested as explanations for the stabilizing effects of lime on soil, cation exchange replacement of existing cations by calcium, flocculation, and carbonation have been prominent. Because many soils in need of stabilization are naturally calcium saturated, flocculated, or both, the first two mechanisms can no longer be seriously considered; and as soil-lime systems sealed from contact with carbon dioxide develop the normal indications of stabilized soils, carbonation must also be rejected.

The effects of lime on soils are such that two stages of reaction can be detected: (1) an early stage in which the plastic properties of the soil are greatly improved but little permanent strength is developed; and (2) a subsequent stage marked by the slow development of strength and the accumulation of soil-lime reaction products. Among the effects in the first state are: (1) large increases in the plastic limit, generally followed by a reduction in the plasticity index; (2) a sharp reduction in the apparent content of clay-size particles as they are bound into flocs stable against the dispersion incident to mechanical analysis; (3) increases in the moisture and the compactive effort required to achieve a given density; and (4) a reduction in such parameters as swell pressure, volume change on drying, and permeability. After the addition of lime, these changes occur in periods ranging from minutes to a few hours.

Based on results of recent work, researchers have suggested the existence of a lime fixation point; that is, an amount of lime that must be added to a given soil to produce the maximum early stage effects, but lime that is not available for further reaction. The mechanism of the effect was discussed in terms of an apparent crowding of excess calcium cations onto the clay following the addition of lime. This in turn was tentatively attributed to pH-dependent exchange sites originating at the edges of the clay particles.

The results of recent experimental work by the authors contradict these hypotheses. The cation crowding effect is in reality one of physical adsorption of calcium hydroxide onto the clay surfaces. The authors postulate that the beneficial effects of the addition of lime are caused by the almost immediate but limited chemical reaction at the points of contact between the edges and faces of primary clay particles within the flocs formed by the normal electrolyte effect of added lime. This reaction is visualized as the formation of small amounts of tetracalcium aluminate hydrate by reaction of the exposed $Al(OH)_x$ groups at the edges of the clay particles with lime sorbed on the faces of adjacent particles. This immediate reaction is supplemented by somewhat slower reaction of the silica with lime to generate tobermorite gel.

The nature of the compounds that are considered responsible for the slow development of strength in soil-lime systems has been discussed in some detail. The exact products formed vary according to the kind of clay and the reaction conditions, especially temperature. At least two phases are produced, a calcium silicate hydrate and a calcium aluminate hydrate. The former is usually tobermorite gel; the latter is a well-crystallized hexagonal compound, which is probably an impure (substituted) tetracalcium aluminate hydrate, and is characterized by a 7.6 A. basal spacing independent of drying conditions. At temperatures only slightly above normal room temperature a different calcium aluminate hydrate—the cubic tricalcium aluminate hexahydrate—is produced.

Quartz, mica, and other phases considered less reactive than clays may also react under appropriate conditions and the result will be similar cementitious products. Quaternary phases in which silicon and aluminum atoms occur in distinguishable lattice positions are not commonly formed, but quaternary phases do occur when lime reacts with previously calcined clay or with the amorphous clay mineral allophane.

Detailed knowledge is lacking on the mechanisms of the chemical reactions that produce the final cementitious products. Evidence exists, however, to show that the reactions are favored by conditions of high pH, which would make silica more soluble; addition of sodium hydroxide to lime-clay systems produces significant strength gains at early ages. This implies a mechanism involving reaction of dissolved silica and alumina with calcium ions. Evidence also exists to show that the reaction is preceded by sorption of the calcium hydroxide from solution and this strongly implies a direct surface reaction with the clay. It may be that both mechanisms are operative.

Rapid Ameliorative Effects

Addition of lime to plastic soils reduces the plasticity index, according to reports of many researchers (*4, 5, 6*). The separate effects of lime on the plastic and liquid limits of plastic soil are discussed individually. Usually an immediate increase in the plastic limit is observed on the addition of lime. The amount of this increase varies directly with the amount of lime added, up to some limiting lime content; further increments of lime usually bring little or no additional increase. The point of inflection of the plot of lime added in relation to the plastic limit has been designated by the appellation "lime fixation point" (*7*). The implications involved in this term will be discussed later.

The effect of the addition of lime on the liquid limit is not so easy to summarize because of conflicting data in published reports. Some authors report decreases in the liquid limit on addition of lime (*4, 5*), others report that this parameter may increase substantially (*8, 9*), and others (*6, 10, 11*) report that both increases and decreases occur, depending on the individual soil being tested. These discrepancies require some explanation. It is known that the liquid limit of a clay is far more sensitive to the kind of cation present than the plastic limit. Calcium-saturated clays have substantially lower liquid limits than the same clays saturated with sodium or certain other cations (*12*). As some—although not complete—cation exchange occurs on addition of lime, the effect of the lime may vary and depends on the extent to which preexisting cations other than calcium are exchanged. Studies on clays of unknown original cation status consequently are difficult to interpret.

Clare and Cruchley (*8*) report data that showed a drastic increase in the liquid limit for a particular clay upon the addition of lime; this clay was almost completely calcium saturated in its natural state. They also state that these data are typical for the other clays tested, in which the original calcium saturation ranged from 35 percent upward. The present writers, and many others, have observed that mixtures of lime and calcium-saturated clay, stored so as to prevent evaporation or carbonation, assume an increasingly dry appearance; sometimes reaction is so extreme that a free-flowing slurry mixture may stiffen so that it will no longer pour or it will not take the shape of the container. This reaction would be reflected by an increase in the liquid limit of the soil. Generally the liquid limit seems to increase on the addition of lime when there is no strong specific tendency in the opposite direction created by cation exchange effects.

When the liquid limit increases on the addition of lime to the soil, the increase usually is not as large as the accompanying increase in the plastic limit. Thus the separate effects of the addition of lime to the soil on the liquid and plastic limits usually combine to result in a rather sharp decrease in the plasticity index. Usually only small percentages of lime are required to produce this sharp decrease in plasticity index, and additional increments of lime are relatively ineffectual. Sometimes, however, addition of the extra increments of lime reverses the trend and produces increases in the plasticity index. Because the plasticity index is a composite parameter an additional complication arises. The plasticity index may not accurately reflect some of the real changes in the system; for example, equal increases in the liquid and plastic limits following a given treatment would be reflected as no change in the plasticity index.

Additional changes generally accompany the aging of the system. Sometimes this aging effect is not large. Lund and Ramsey (*6*), for example, reported that very little change occurred in the Atterberg limit values of soil-lime mixtures after the first hour. However, often substantial time-dependent changes do ensue. For example, Wolfe and Allen (*13*) reported substantial increases in plasticity index for lime-soil mixtures cured for 2 days, as compared with mixtures tested immediately after the addition of lime. When the curing periods were extended from 2 days to a period of 7 to 28 days, the effect was reversed, and significant decreases in plasticity index were recorded; a nonplastic condition was recorded for most of the lime-soil mixtures tested.

Grain-size distribution

Changes in the effective grain-size distribution occur almost immediately following the addition of lime to a clay soil. Data obtained by conventional sieve and hydrometer analysis show that a major decrease in the content of clay-size particles occurs within the first hour; subsequent results obtained after periods ranging from 1 hour up to 240 days show only small additional changes (*6*). The new grains produced as a result of the lime treatment are mostly sand size and, although relatively weakly bonded, are for the most part capable of withstanding a 5-minute dispersion period in a mechanical mixer (*6*, *13*).

Moisture-density relations

Many researchers have reported that the density to which a soil can be compacted at a given moisture content is usually reduced significantly when lime is added, and delay in compaction causes a further reduction in density. To achieve maximum density for a given compactive effort the required moisture content usually increases, sometimes rather significantly. However, according to results summarized by Herrin and Mitchell (*14*), lime in excess of a relatively limited amount, on the order of 5 percent by weight of soil, generally causes little additional increase in the optimum moisture requirement.

Volume change effects

Lund and Ramsey (*6*) reported a drastic reduction in the volume change. This effect was observed within the first hour after the addition of lime, and the soil test showed that about 3 percent of lime was sufficient to obtain the maximum volume change effect. A corresponding immediate increase occurred in the shrinkage limit itself. Similar results were reported by Wolfe and Allen (*13*). Mitchell and Hooper (*15*) reported that lime, specifically dolomitic lime, markedly reduced the swelling of specimens tested under a modest surcharge pressure. The effect was observed after an aging period of 24 hours. A reduction in expansion pressure on addition of lime was observed by Wolfe and Allen for some soils, but not for others (*13*).

Clare and Cruchley (*8*) reported significant increases in the amount of moisture held against a given suction after the addition of lime.

Permeability

Although few data are available, the permeability of compacted soil-lime mixtures has been reported to be much less than that of compacted soil alone (*13*).

These different short-term effects can be regarded as different aspects of the ameliorative effect that lime has on the properties of clay soils. The authors attempt to define herein exactly what chemical or physico-chemical action is being reflected in these sometimes drastic changes. Considerable evidence seems to point to the conclusion that these rapid responses are not the result of the pozzolanic reactions to which permanent strength gains are attributed. It has been well documented that the development of strength of specimens, particularly after their having been soaked, is a fair index of the amount of cementitious compounds formed (*16*). The experience of many researchers summarized by Herrin and Mitchell (*14*) and the results documented by Anday (*17*) indicate that strength development in soil-lime systems is a comparatively slow process that characteristically requires from several weeks to many months at normal temperatures.

Mitchell and Hooper (*15*) pointed out that, if significant amounts of lime were consumed by permanent cementing reactions at early ages, delay between mixing and compaction should adversely affect the final strength of the soil. But, when all of their lime-soil samples were compacted to the same density, no adverse effect on the final strength was recorded for delays of up to a day between mixing and compacting. Similarly, if significant permanent cementing were to occur at early ages, subsequent remolding of the specimen should bring about a strong reduction in the ultimate strength developed.

Data developed by F. D. Shepard in 1963 in a study made at the laboratories of the Virginia Council of Highway Investigation and Research, Charlottesville, Va., showed that remolding soil-lime mixtures as long as a week after initial compaction caused no deleterious effect on the ultimate strength. But Shepard's data also show that when soil-cement specimens, in which cementation occurs rapidly because of hydration, were remolded after a week of curing, their ultimate strength was markedly reduced. Thus, extensive development of pozzolanic reaction products seems also to be ruled out as a mechanism responsible for the rapid improvement of the properties of plastic soils when lime is added.

Lime Fixation Point

Extensive investigations undertaken at Iowa State University (*7*, *18*, *19*, *20*, *21*, *22*) have led to the concept of the lime fixation point. This point was defined as one at which the percentage of lime is such that additional increments of lime produce no appreciable increase in the plastic limit. It was hypothesized that excess calcium cations, derived from the lime, in some fashion crowd onto the clay particles and cause them to become electrically attracted—a process causing flocculation in which weak bonds exist between the flocs. Additional lime, which produces calcium cations in excess of those that can crowd onto the clay, produces no further change in the plastic limit. Calcium held by the clay in amounts up to the lime fixation point was considered to be immune to further reaction with the clay to form cementitious compounds. The sedimentation velocity of flocs formed by adding lime to a clay suspension reached a maximum near the lime fixation point, indicating that floc size was at a maximum at this point (*20*).

Ho and Handy (*21*) cited evidence that calcium was retained by bentonite from lime-bentonite slurries after a very limited washing treatment. The amount of calcium retained increased as the percentage of lime in the slurry was increased, and for modest percentages of lime the retained calcium was far more than the normal cation-exchange capacity of the clay. These authors (*21*) hypothesized that the calcium in excess of the normal cation-exchange capacity was held at new exchange sites generated at the edges of clay particles by the increasing dissociation of acidic ($\underline{\quad\quad}Si(OH)_x$) groups as the pH increased; hence the term pH-dependent exchange. However, they noted, without explanation, that the amount of calcium retained continued to increase steadily as increments of lime were added far beyond the lime fixation point and no break in the curve was evident.

Ho and Handy (*21*) also studied several other features of the lime-bentonite system. Small additions of lime (up to about 2.2 percent by weight of clay) increased the relative viscosity of calcium bentonite slurries; however, as aging of the soil samples increased, a continual increase was required in the lime content to attain maximum relative viscosity. These authors also made differential thermal studies of dried lime-bentonite slurries, and stated that samples to which only a small amount of lime had been added failed to generate the normal endothermic response characteristic of the lime.

Ho and Handy (*22*) also reported the results of measurements of the zeta potential—a quantity related to the net negative or positive charge carried by the clay particles in dilute suspension—of lime-treated bentonite aged either for several days (fresh) or for a year (aged). Calcium-saturated bentonite had a zeta potential of about -20 millivolts. Small additions of lime caused a slight increase in this potential, and larger additions generated a modest decrease that was identical for both fresh and aged samples. Sodium-saturated bentonite had a zeta potential cf about -40 millivolts; additions of lime to this clay up to about 6 percent caused strong proportional reductions to -26 millivolts for the fresh samples and -22 millivolts for the aged samples, and larger additions of lime caused no further change. The authors of this article do not agree with Ho and Handy's interpretation of their results but attribute the large effect reported for the sodium bentonite to the ordinary process of cation exchange of calcium for sodium. This exchange, in accord with the results reported earlier by Prikryl and Esterka (*2*), was not entirely complete.

The authors are not satisfied that the interpretations of the early ameliorative effects of lime on clay suggested by the Iowa State University researchers could be correct in detail. The apparently unlimited crowding of positively charged cations onto the limited external surface of the montmorillonite seems to be an unlikely phenomenon; if it were to occur, a large decrease and eventual reversal of the negative charge of the clay would be expected to take place because of the limited number of ____ $Si(OH)_x$ groups on the edges of the clay particles that could dissociate to generate negative charges to balance the cation uptake. A series of investigations was therefore carried out in an attempt to obtain more information about these matters. Details of these investigations are not presented here, but some of the results have been summarized.

Results of Investigations

Measurements were carried out on Wyoming bentonite, which had been saturated with calcium cations by standard laboratory procedures and checked for completeness of saturation. Small quantities of the calcium-saturated clay were then shaken with a large amount of saturated calcium hydroxide solution for different periods of time at room temperature, and the clay was separated by centrifugation. The supernatant solutions were recovered and promptly analyzed for calcium content by versenate titration and for hydroxyl content by titration against standard acid. The results listed in the following paragraphs were obtained.

- A very rapid reduction occurred in the concentration of both calcium and hydroxyl ions in the solution.
- The proportion of the ions remaining in solution was stoichiometric, thus indicating that equivalent proportions of hydroxyl and calcium ions—two hydroxyl ions for each calcium ion—had been taken up by the clay.
- About 3 percent of lime by weight of the clay was adsorbed within the first 5 minutes, the minimum time in which it was possible to perform the manipulations. This amount corresponds roughly to the lime fixation point of the Iowa State researchers.
- Further sorption continued at a declining rate for the 3 weeks that the experiments were continued. At that time, the total amount of lime removed from the solution amounted to about 20 percent of the weight of the clay.
- When the centrifugally separated clay was washed with an amount of distilled water equal to the volume of the saturated lime solution originally used, essentially complete removal of the adsorbed lime was obtained if the washing was done shortly after the onset of the experiment. However, the ratio of hydroxyl to calcium ions removed was slightly less than stoichiometric.
- After a sample had been in contact with the lime solution for several days and had adsorbed considerable additional lime, a single wash, as outline in the preceding paragraph, removed only part of the lime; subsequent washings removed smaller and smaller amounts of lime. The ratio of hydroxyl to calcium ions removed in successive washings declined from values fairly close to stoichiometric (about 1.7) to about 1.
- In differential thermal analysis (DTA) of dried clay, which had sorbed about 4 percent of lime from solution in about an hour of contact, no lime was detected. A mechanical mixture of dry clay containing the same amount of dry lime produced a readily detectable endothermic response at 500° C., which is a response characteristic of crystalline lime.
- No peaks for crystalline calcium hydroxide were observed on the X-ray diffraction pattern of the clay recovered from the lime solution; the corresponding dry mixture produced easily detectable peaks under the same diffraction conditions.
- Measurements of surface charge of the calcium bentonite were carried out on untreated clay and on clay recovered after its immersion in saturated lime solution for an hour. The method used was the one Pike and Hubbard used for a similar determination of the surface charge of hydrating cement particles (*23*). No significant change in negative charge was recorded.

In other experiments, lime was added to suspensions of calcium-saturated bentonite of restricted water content. At lime contents of 4 percent or less by weight of clay, the electrical conductivity of the suspension decreased to very low values in less than 24 hours. This was regarded as an indication that the lime was being rapidly adsorbed, accompanied by a consequent decrease in concentration of the lime electrolyte in the pore solution. Removal of some of the pore solution by high-speed centrifugation and subsequent chemical analysis confirmed this interpretation. The response to lime in clay-water systems of restricted water content was similar to that occurring in dilute suspensions.

There was no evidence of heat production or heat removal accompanying the addition of lime to calcium bentonite suspensions of restricted water content, in tests carried out over several hours with a moderately sensitive calorimeter. This finding is considered to be further indication that the lime sorption process is one of physical adsorption rather than chemical reaction.

Interpretations

The results on the early soil-lime reactions have been interpreted by the authors somewhat differently than has been reported by others. The evidence cited permits the following interpretations:

- Calcium hydroxide is physically adsorbed from solution at a very rapid rate by calcium-saturated clay and, presumably, also by clay saturated by other cations. This adsorption is largely reversible at very early stages of reaction, but adsorption is soon followed by a reaction that produces calcium silicate hydrates. The conclusion that lime is physically adsorbed on clay surfaces was also reached by Prikryl and Esterka (*2*).
- The adsorption removes calcium ions and hydroxyl ions from solution concurrently and does not reflect a crowding of cations only onto new exchange sites generated at high pH levels, as previously postulated by others.
- As both ions are sorbed in equivalent amounts (within the limits of the accuracy of the analysis), no significant change occurs in the net negative charge of the clay particles. This does not preclude small changes in the zeta potential after chemical reaction has proceeded for some period of time.
- The amount of calcium and hydroxyl ions sorbed immediately—about 3 percent by weight of clay—would correspond roughly to sorption of a little more than a monomolecular layer of calcium hydroxide on the external surfaces of the clay. This sorption corresponds roughly to the lime fixation point, and it is suggested therefore that the latter represents approximately a monolayer of lime on the external surfaces of the particular clay.
- The very large amount of slow sorption beyond the amount rapidly sorbed is believed by the authors to reflect several additional processes, but principally the process of slow reaction of adsorbed lime with the clay surfaces to produce calcium silicate and calcium aluminate hydrates. The authors also believe that, at least in wet systems, these products spall from the clay surface, thus liberating fresh clay surface for further adsorption and reaction. Physical adsorption of lime onto the newly formed reaction products is also likely. Finally, a slow, restricted entry of lime into the interlayer spaces of the clay may take place.

Mechanisms of Rapid Reaction

The observation that adsorption of lime occurs in clay-lime systems does not in itself provide any particular indication of how the clay properties are so drastically changed within a short time after the addition of lime. The mechanics of this process require additional explanation and clarification.

Strong flocculation is commonly observed when lime is added to clay. In general, according to current colloid-chemical concepts (*24*), a clay flocculates on addition of an electrolyte because of the modifiying effect of the electrolyte on the extension of the electrical double layer from the surfaces of the clay particles. The electrolyte represses the double layer and thus reduces the electrostatic repulsive forces between clay particles. The result is a net attraction, especially between negatively charged faces and positively charged edges of adjacent particles, and a cardhouse or double-T structure develops. If the electrolyte is removed from the pore solution, the double layer again spreads out, the repulsive forces between particles increase, the flocs weaken and are reduced in size, and eventually the system deflocculates.

In the experiments partially reported here, removal of lime by adsorption from the pore solution after a few hours caused very low concentrations of electrolyte; yet the initially formed flocs persisted and became, if anything, more pronounced and stable with lapse of time. Obviously, the lime has more profoundly altered the properties of the clay than can be explained by the flocculation effects of electrolytes described here.

One of the authors previously has demonstrated (*25*) that lime reacts almost instantaneously with hydrous alumina of high-surface area to generate the well-crystallized compound tetracalcium aluminate hydrate, C_4AH_{13}. (In the shorthand notation commonly used for these compounds: C = CaO, A = Al_2O_3, H = H_2O, S = SiO_2.) This compound is also probably formed on the hydration of C_3A in portland cement (*26*). In this article the authors postulate that in lime-clay systems a similar immediate reaction takes place between the alumina-bearing edges of the clay particles and the lime adsorbed on the clay surfaces.

In particular, the postulation is that this reaction occurs at the points of contact between the edges of one particle and the faces of adjacent particles in the cardhouse structure of the flocs. Calcium silicate hydrate (tobermorite gel) probably forms at these points of contact also, but slowly, perhaps over a period of some hours. Formation of very small quantities of these cementing products at the points of contact is believed to be sufficient to stabilize the flocs and knit the particles together so that plasticity, shrinking and swelling, and other normal clay-water interactions are distinctly inhibited. The individual particles are cemented together well enough within the flocs to resist dispersion, and the flocs may act as single grains in mechanical analysis (*6*). However, the flocs were not bonded to each other well enough to provide significant strength in the overall clay mass, and thus the clay has been ameliorated but not really stabilized.

To develop such a stabilized material capable of holding together and resisting applied loads, compaction is required to obtain a minimum volume of voids, and a sufficient length of time must be permitted for the slow continuing chemical reaction to develop enough additional cementing products to fill the voids at least partially. As shown by Jambor (*16*) the strength developed in lime-pozzolan systems depends to some extent on the kind of cementing agent formed, but also in great degree on the proportion of void space occupied by the cementing agent—the *gel-space ratio* familiar in portland cement technology.

The formation of calcium aluminate and calcium silicate hydrates at particle contacts very early in the reaction process cannot be easily demonstrated because of the very small amounts of these products involved and the nature of the system. The concept is offered as a working hypothesis consistent with the known properties of the system.

Products of Long-Term Reaction

The reactions that occur over a long period of time and are, in the last analysis, responsible for the stabilization of the soil, are of at least as much concern as the ameliorative responses just described. Most soils consist largely of uncombined silica and of silicates of many kinds; alumino-silicates usually predominate in the clay fraction. Consequently, it is not surprising that reaction with lime produces compounds largely of two classes: hydrated calcium silicates and hydrated calcium aluminates.

Except when formed under hydrothermal conditions, the calcium silicate hydrates are invariably poorly crystallized and difficult to detect. Three such phases are known in the literature: tobermorite gel—also called C-S-H gel—and the phases known as C-S-H(I) and C-S-H(II). The gel is a high-calcium phase normally generated in and responsibile for the strength of portland cement concrete. Of the three phases, C-S-H (I) has a distinctly lower calcium content, a somewhat different morphology, and can be distinguished by a very strong exothermic peak that occurs at about 850° C. on DTA. Although C-S-H(I) may be synthesized in a fairly well-crystallized form in the laboratory, the gel phase is invariably much less well crystallized, and it has a maximum of only three X-ray diffraction peaks. C-S-H(II) is a high-calcium phase, whose exact properties are open to some doubt. All of these compounds are presumed to have a layer structure similar to, but not necessarily identical to, that of the well-crystallized mineral tobermorite. The latter may be synthesized readily by hydrothermal means, but its occurrence in soil-lime reaction products produced under normal atmospheric conditions is extremely unlikely.

There are several types of calcium aluminate hydrates. The one commonly formed at normal temperatures is a member of the tetracalcium aluminate hydrate group. This group comprises many crystalline modifications and partially dehydrated states, as well as phases of the same basic structure, but carbonate groups are incorporated in place of some of the hydroxyls. The form generally produced by clay-lime reactions is most similar to a phase in which the composition is $C_4AH_{12}\cdot CO_2$, and it has a basal spacing of 7.6 A. that is not changed by drying. In contrast, pure C_4AH_{13} has a basal spacing of 7.9 A. when moist, and the spacing diminishes stepwise to about 7.4 A. or less upon drying. It is possible that the soil-lime product may incorporate some silicon in isomorphous substitution for aluminum.

Reactions of lime with clay minerals at slightly elevated temperatures generally produce a very different calcium aluminate hydrate, C_3AH_6. This is a cubic phase having a crystal structure different from that of the tetracalcium aluminate hydrates; it forms preferentially at temperatures above about 30° C., and once formed is stable at room temperature. A recent monograph edited by Taylor (*27*) covers the status of knowledge of both calcium silicate and calcium aluminate hydrates.

Goldberg and Klein (*28*) carried out the first published X-ray study of lime-clay reaction products, but detected only calcium carbonate, which was probably produced during air drying of the sample prior to its being X-rayed. Eades and Grim (*29*) reported that reaction of lime with pure clay minerals at 60° C. caused the formation of new minerals. Kaolinite so treated yielded peaks for a poorly crystallized calcium silicate hydrate of unspecified type, and a peak of 5.1 A. (and others), which the present writers interpret as having been caused by C_3AH_6. Eades and Grim could not detect any new crystalline product of lime-montmorillonite reaction, although it was obvious that reaction had occurred. Illite reacted somewhat, but no positive statement was made as to the nature of the reaction product or products.

Hilt and Davidson (*30*) examined the product of a long-term reaction of lime and montmorillonite at room temperature, and finally identified it as a C_4AH_{13} type of material. Its properties were consistent with the previously mentioned product having a 7.6 A. spacing. The published X-ray diffractometer traces indicated weak peaks that were attributed to pooly crystallized calcium silicate hydrates. Glenn and Handy (*31*) studied the products of reaction between several clay minerals and different forms of lime at room temperature, but their results were not completely interpreted. They reported generally that poorly crystallized calcium silicate hydrates and the 7.6 A. calcium aluminate hydrate were found in the kaolinite systems; in addition, an unknown 12.6 A. compound was formed when dolomitic lime was used. Montmorillonite yielded both the 7.6 A. calcium aluminate hydrate and materials whose diffraction peaks were ascribed by the authors to a more nearly pure C_4AH_{13} phase.

Glenn and Handy observed no reaction of lime with quartz, and little with muscovite or vermiculite. In contrast, in studies of the products formed in field soil stabilization projects, Eades, Nichols, and Grim (*3*) reported that considerable reaction had occurred in quartz- and mica-bearing soils. When examined under the petrographic microscope, the quartz and mica particles had developed fuzzy outlines and visible cementing gel was present, not only as a coating on the grains but also in cracks within the grains. Examination by X-ray diffraction disclosed the presence of calcium silicate hydrates, as well as calcium carbonate. The possibility that calcium aluminate hydrates might also have been formed was not discussed.

Diamond, White, and Dolch (*33*) reported that kaolinite and montmorillonite reacted with lime to produce different products under different reaction conditions. At 60° C. both clays produced calcium silicate hydrate classified as C-S-H(I) and the kaolinite produced the cubic C_3AH_6; no crystalline calcium aluminate compound was formed from montmorillonite. At lower temperatures the products from both clays were considered to be tobermorite gel and the 7.6 A. calcium aluminate hydrate. Small peaks at about 9 A. occurred in the montmorillonite products under both conditions; but they disappeared when the products were washed and no explanation for their presence could be offered. These authors reported that both the tobermorite gel and the 7.6 A. calcium aluminate hydrate product were formed by reaction of lime with mica, illite, and even pyrophyllite. Reaction with quartz generated tobermorite gel even at 60° C.

In a paper titled, *X-Ray Studies of Lime-Bentonite Reaction Products*, G. R. Glenn and R. L. Handy reported further results on long-term studies of reaction products of lime and montmorillonite at room temperature at the 66th annual meeting of the American Ceramic Society held in Chicago, Ill., 1964. In general, the formation of tobermorite gel, C-S-H(I), C_4AH_{13}, and possibly C-S-H(II) were reported. Interestingly, fresh mixtures of clay and lime, as well as mixtures that had been allowed to react at room temperature for several years, yielded only well-crystallized tobermorite on hydrothermal treatment. The aluminum present in the product was believed to have been incorporated as an isomorphous replacement for silicon within the tobermorite lattice.

In all the studies discussed so far, no quaternary compounds (that is, compounds in the lime-silica-alumina-water system) were reported. Apparently, where separate calcium aluminate phases were not developed, the aluminum present was incorporated isomorphously in the calcium silicate phase. In contrast to these results, Benton (*33*) reported that reactions of lime with calcined kaolinite yielded the quaternary compound gehlenite hydrate, C_2AS_x, also called Stratling's compound. This compound was formed in addition to the more usual products, a poorly crystallized calcium silicate hydrate and the 7.6 A. calcium aluminate hydrate.

In a Japanese study (*34*) the same gehlenite hydrate and the 7.6 A. calcium aluminate hydrate were reported as the result of reactions at normal temperatures between lime and Kanto loam soils, which consist mostly of the amorphous clay mineral allophane. At higher temperatures the same soils produced C_3AH_6 and a hydrogarnet quaternary phase instead of these compounds. When gypsum was also included in the treatment of these soils with lime, excellent stabilization results were obtained: the major cementing agent formed was ettringite or so-called *cement bacillus*, a sulfate-bearing phase formed in hydrating cements.

Cementation Products

The early physico-chemical reactions of lime that produce the ameliorative effects on soil clays, and the nature of the cementing compounds that produce the final cemented product have been discussed, but little has been said about the mechanics of the chemical and structural transformations that generate the final compounds. Very little is known about the details of the reaction processes involved, and most information is speculative in nature. This lack of knowledge is one of the major gaps in understanding the soil-lime system.

Eades and Grim (*29*) have suggested that with kaolinite, ". . . the reaction seems to take place by lime eating into the kaolinite particles around the edges with a new phase forming around a core of kaolinite." Electron micrographs by Diamond, White, and Dolch (*32*) tend to confirm this idea because the edges of residual kaolinite particles were ragged and irregular, as though they had been attacked chemically. The probability that partial exfoliation had taken place also was proposed by Diamond et al; they also called attention to the fact that because two distinct crystalline hydration products were produced, a simple topotactic solid-state mechanism was not a reasonable explanation.

At the 1st annual meeting of the Clay Minerals Society (1964) held in Madison, Wis., R. L. Sloan presented a paper, *Early Reaction Determination in Two Hydroxide-Kaolinite Systems by Electron Microscopy and Diffraction*, in which he reported an electron-microscope study of the effects of treating kaolinite with sodium hydroxide and also with dilute lime in suspensions. He confirmed that under such conditions the primary attack on the kaolinite particles took place at the particle edges. When lime was used, he observed what appeared to be nucleation of a reaction product at or near the edges of the kaolinite particles; however, this product did not seem to be one previously reported as occurring in lime-clay reactions, and the exact significance of this observation is uncertain.

For illite and montmorillonite soils, Eades and Grim concluded that ". . . Following the saturation of the interlayer positions with calcium ions the whole clay mineral structure deteriorates without the formation of substantial new crystalline phases." In contrast, Diamond, White, and Dolch reported that new crystalline phases (tobermorite gel and the 7.6 A. calcium aluminate hydrate) were formed from these two minerals, and even in advanced stages of the reaction when most of the clay had been decomposed, the clay that remained retained its crystallinity almost intact. For example, a 2M illite retained all the X-ray peaks characteristic of this polymorph, and montmorillonite retained its characteristic (060) spacing.

Eades, Nichols, and Grim (*3*) suggested that a pH high enough to dissolve silica is an essential feature of the process of formation of calcium silicate hydrates by lime-clay reactions; this idea was seconded by Diamond, White, and Dolch (*32*) who envisioned the solution from the edges of the clay crystals as a possible mode of reaction. The addition of sodium hydroxide to a lime-soil mixture has been reported to accelerate strength development (*35, 13*). Moh (*36*) bases his explanation of these benefits in both soil-lime and soil-cement systems partly on the hypothesis of an increased rate of the solubility of potentially reactive silica.

The preceding arguments imply that the reaction path in lime-soil stabilization proceeds through solution—that silica liberated from the clay reacts with dissolved lime. In contrast, results of tests by the authors seem to suggest that reaction proceeds between adsorbed lime and the surface layers of the clay with which it is in contact. Such a mechanism has been proposed to account for the rapid generation of tobermorite gel by lime sorbed on silica gel surfaces at moderately elevated temperatures (*37*). Perhaps, as seems to be so in portland cement hydration, both *adsorbed-state* and *through-solution* reactions take place, both contributing to the development of the final product. However, a firm decision as to the reaction path awaits additional intensive experiments.

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(Continued on p. 273)

Experimental Isolation of Drivers' Visual Input

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

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Lack of scientific knowledge as to what features of the road and terrain drivers respond to prompted the study reported in this article. In an attempt to determine what these features might be, an experiment was conducted to measure drivers' visual inputs when their vision was isolated by a limiting aperture device. Use of this technique forced the driver to look for portions of the road from which he could get this essential information.

In the experiment, the shifts in fixation of the drivers' eyes emphasized the requirements of perceptual anticipation and vehicular alinement in which the driver must look far ahead to obtain a general idea of conditions that he will have to meet and at the same time keep his vehicle alined on the road by closeup viewing. Results obtained in the study indicate that the driver obtains this information from viewing the edges and centerline of the road. On this basis, edge markings are recommended where contrast is low or where night usage is heavy and a centerline is recommended, especially where two-way traffic is heavy.

Introduction

AN UNDERSTANDING of the driver's visual input provides a rational basis for many aspects of highway design. When the information that the driver uses is known, roads can be designed so that he will receive this information. As no experimental technique existed by which the visual factors in driving could be isolated, their nature primarily has been the subject of conjecture. From a scientific viewpoint, the isolation of visual input is both important and baffling. This information, used by the driver, sets off an action sequence of steering, braking, and acceleration of the car itself. Unless the stimulus that first triggers the driver's reactions is known, the consequent reactions are not easily understood. And when man's input has been specified, driving itself will be to a considerable extent described. The problem is difficult: The binocular field presents an enormous amount of information, but lack of communication lines to the driver's eyes or brain prevents a determination of how he selects and sorts this sensory input. If a driver is asked what he is responding to, suggestive, but in no sense trustworthy, answers are obtained.

A technique to determine what features of the road and terrain the driver is responding to is discussed in this article. The method involved having the driver guide the car while looking through a device containing a small aperture. By decreasing the visual field, the essential information, whatever it was, could not be seen at the same time: The driver was forced to obtain information in separate visual fixations. A continuous film record was made of the driver's field of view, and later it was analyzed to determine the center of his visual aim and the content of each fixation. The essential information he was using could be easily identified in each separate restricted fixation. This technique also may be used to determine the aircraft pilot's perceptual input and may be applicable, with modifications, to problems of human console design. Use of the aperture method was more advantageous than use of eye camera techniques, which provide a record of fixation position. The eye camera does not show the contribution of peripheral vision, and it does not provide a means for distinguishing essential from nonessential information.

Background

Different types of information have been suggested as being the inputs of driving (*1, 2, 3*).[3] A ranking of inputs made by a race driver and the editor of a scientific magazine, who evaluated their responses as drivers, to conspicuous features of the environment, may be taken as representative (*4*).

The race driver and the editor ranked the inputs to which they responded in the following order:

race driver		editor
View of the road ahead..	1.....	View of the road ahead.
Seat-of-the-pants feel (transverse accelerations).	2.....	View of the car ahead.
Tachometer............	3	Feel of steering wheel.
Feel of steering wheel....	4.....	View of the road edge.
Engine sound..........	5.....	Speedometer.
View of the road behind.	6.....	View of the road behind.
Oil-pressure gage........	7.....	Seat-of-the-pants feel (transverse accelerations).
View of the car ahead....	8.....	Engine sound.
View of the road edge....	9.....	Blinking lights.
Smells..................	10....	Tire noise.
Tire noise..............	11....	Smells.
Blinking lights..........	12....	Oil-pressure gage.
Speedometer............	13....	....

The race driver and the scientific editor agreed that the view of the road ahead ranked first in affecting driver behavior. Otherwise, their ranking of environmental factors did not agree. This disagreement probably reflected a real difference in approach to driving. Obviously, a rigorous experimental method is required to determine what the driver is actually looking at and responding to. (Michaels and Cozan (*3*) have been perhaps the first to use rigorous experimental methods to validate a driving input. In field tests using lateral movement detectors, they showed that the driving response is inversely related to the sidewise drift of the approaching object or vehicle.)

Apparatus

An aperture device was developed that restricted the driver's vision and recorded his visual fixation positions. The main parts of this device are a head helmet, an aperture observation tube, and a camera. They are described in the following paragraphs and illustrated by figure 1.

A large plastic football helmet with frame supports was used to hold aperture and fiberglass pulpit. An inflatable bladder filled the space between helmet and head and held the helmet firmly in place.

An aperture observation tube 3½ inches in length and 1 inch in diameter was used. The tube could be raised or lowered to accommodate the observer's eye. Aperture disks of varying size could be fitted on the end of the tube. A circular screen covered the peripheral areas of the driver's field, and an eye patch fitted on his unused eye.

An 8-mm. camera was mounted coaxially with the aperture tube. The camera had an automatic (photoelectric) shutter and a battery-powered feed. The zoom lens was set at 8-mm. focal length. Speed of camera was slowed to 11 frames per second. The 25-foot film roll gave 178 seconds of record. This was enough to cover the experimental course.

Drivers

Ten volunteers (seven male, three female) from the Bureau of Public Roads served as test drivers. All subjects had vision rated sufficiently good to drive without glasses. The age of the drivers ranged from 19 to 38 years and the mean of their ages was 27.7. The years of driving experience of the volunteers ranged from 1 to 24 and the mean was 10.3.

Driving Course and Test Vehicle

A curved 2-lane road at the Herbert S. Fairbank Research Station, McLean, Va., where traffic density is low, was used as the test course. Figure 2 illustrates the test course: It was 22 feet wide, had a center yellow strip 4 inches wide, and was paved in blacktop. The shoulders of the road were planted in grass. The 2,805-foot length included a left

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[1] Presented at the 44th annual meeting of the Highway Research Board, Washington, D.C., January 1965.

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[3] References indicated by italic numbers in parentheses are listed on p. 273.

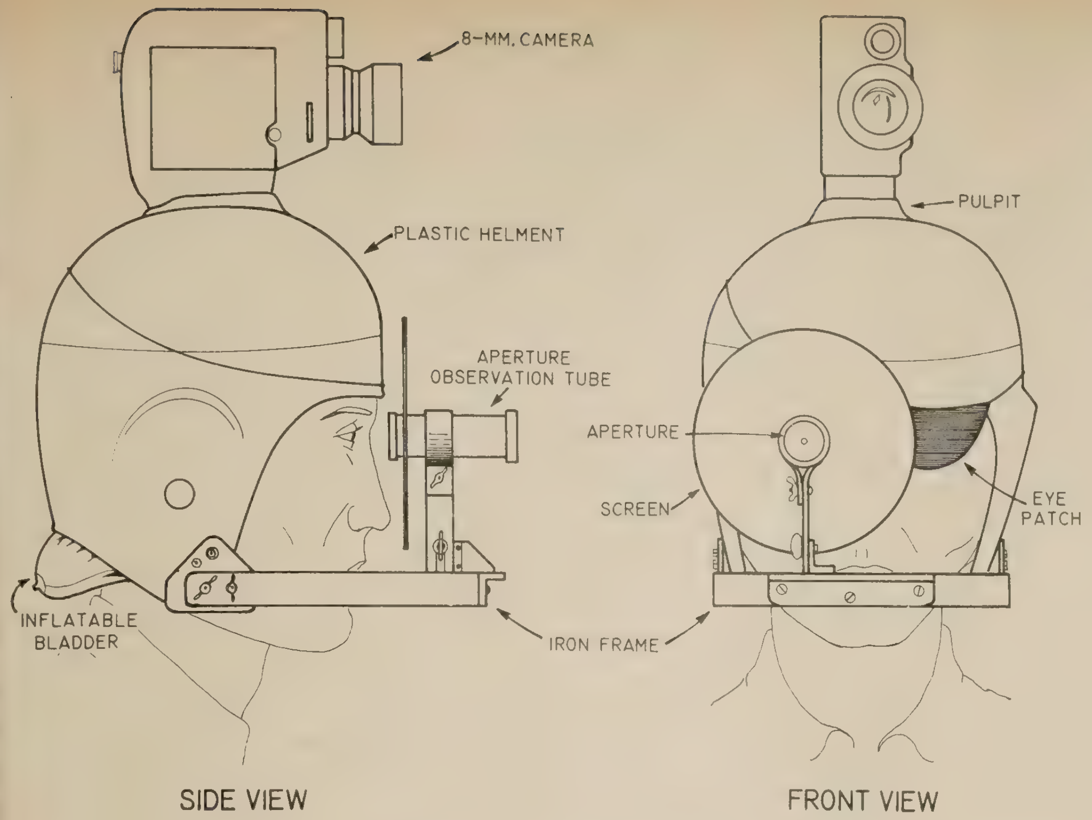

Figure 1.—Aperture device.

and a right curve. A carryall station wagon was used as the test vehicle. To obtain headroom for the helmet, the front seat of the vehicle was removed and a low cushion substituted for it. The test drivers could see over the hood without difficulty.

Procedure

The procedure included both practice and experimental phases. The program of these phases was carried out in a single 1-hour session, the procedure program is described in the following paragraphs.

The driver was instructed that he would be required to guide the car while his vision was restricted. He then practiced on a curved and hilly practice course, first without the aperture device and later with it. After practice, he was asked three questions:

- On the left curves, what did you look at mainly?
- On the right curves, what did you look at mainly?
- Was there any consistent pattern of movement of fixations from side to side or backward and forward that you adopted?

The driver operated in the experimental phase with: (1) open vision; (2) a large aperture of 9¾°; and (3) a small aperture of 4°. The open viewing was intended to provide a comparison of aperture driving with normal driving. The observer continually reported his visual fixation position on a tape recorder. After driving with open viewing, the drivers were asked the same three questions used in practice procedure.

Data collected during large aperture viewing were compared with data obtained during the small aperture viewing and an analysis made on the effect of size of viewing aperture. The procedure included calibration of the aperture device as well as data collection. The aperture device was calibrated for each driver by having the driver center in the aperture on a 2-inch square of white paper that was taped to a tree 50 feet away. Wooden uprights were adjusted until they appeared exactly on the left and right limits of the driver's field of view, as shown in figure 3. A brief film record of the adjustment was made for each driver and he was cautioned not to shake the helmet. The film was used as a record of the center and outer limits of each driver's field of view. As the driver drove the test course a continuous film record of his visual fixations and a tape recording of his verbal identifications of position were made. Camera and tape recordings were synchronized by the experimenter periodically interrupting the lens field and simultaneously recording an auditory signal. When the driver had completed the test run he was again asked the three questions.

The small aperture viewing was used to test the driver's visual behavior under the stress of limited information. The procedure used with the small aperture was essentially the same as that used with the larger aperture. Four drivers started at the A end of the track and four started at point B, as shown on figure 2. Two patterns of starting were used for each of the two groups of five drivers. The sequence of starting points was:

1st group	2d group
Open viewing—A, B, A	Open viewing—B, A, B
Large aperture—B, A, B	Large aperture—A, B, A
Small aperture—A, B, A	Small aperture—B, A, B

This variation in starting positions provided a replication of the procedure.

Analysis—Fixation Area and Fixation Position

Each driver's record was divided into separate fixations; that is, visual positions held until another was clearly assumed. Duration of each fixation was determined from the length shown on the film divided by known rate of film movement. A total of 3,305 separate fixations was analyzed on 4,152 inches of film recorded by the 10 drivers. The records were analyzed for fixation area and fixation position.

The area of fixation described the most inclusive road region covered in the small or large aperture. The sample areas are illustrated in figure 4. A response of the "whole road" area implied that both left and right edges of the road were included in the fixation. The "left lane" response included the left edge and centerline, and the "right lane" response covered the centerline and right edge. The designation for "yellow line," "left shoulder," and "right shoulder" applied to these features

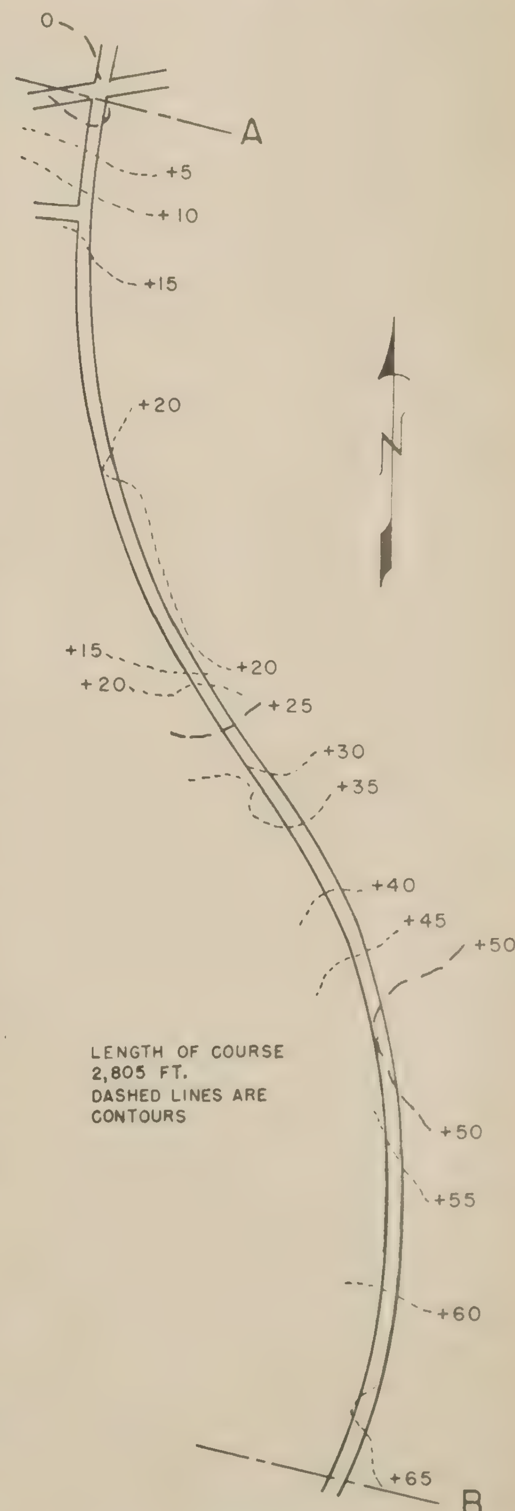

Figure 2.—Experimental course.

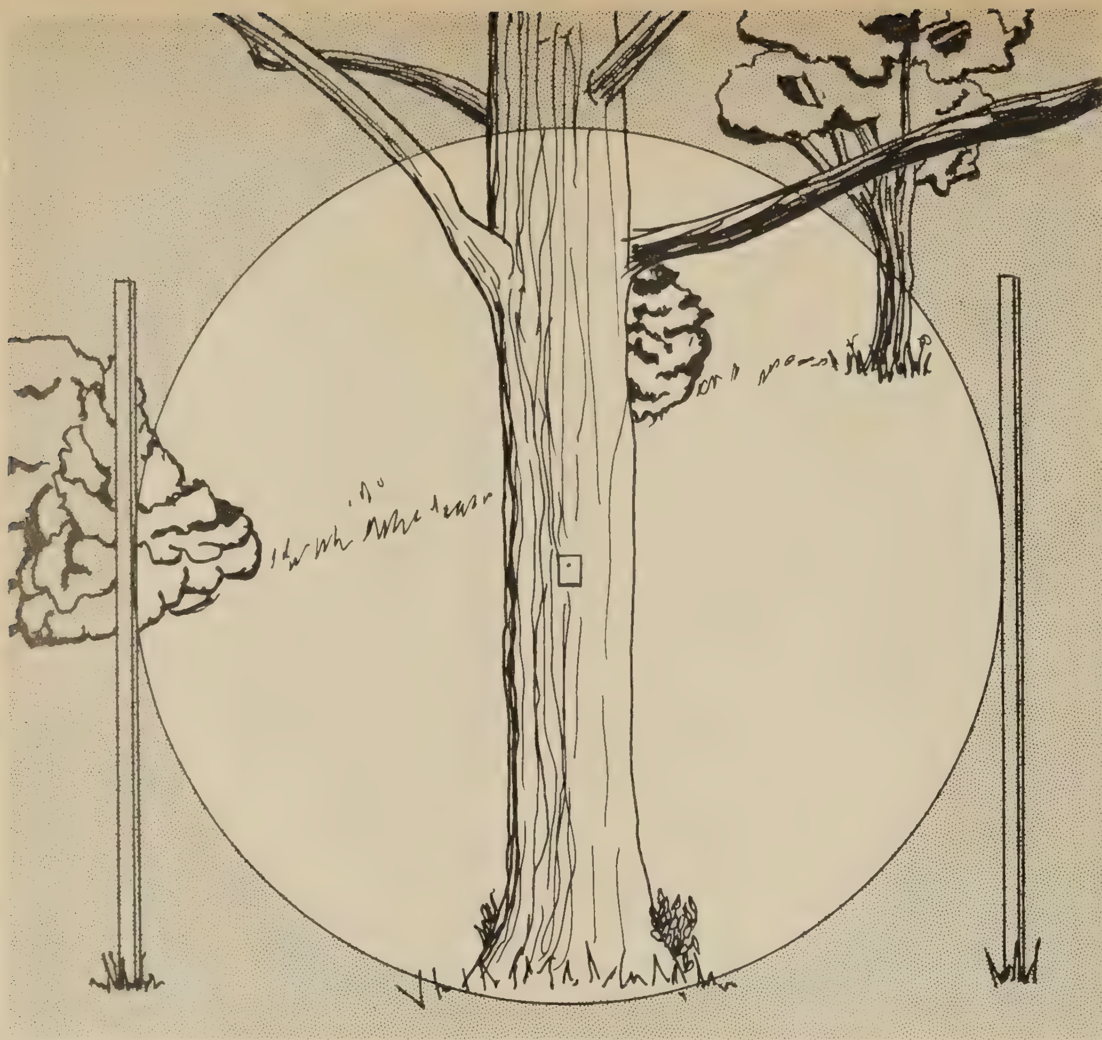

Figure 3.—Calibration arrangement.

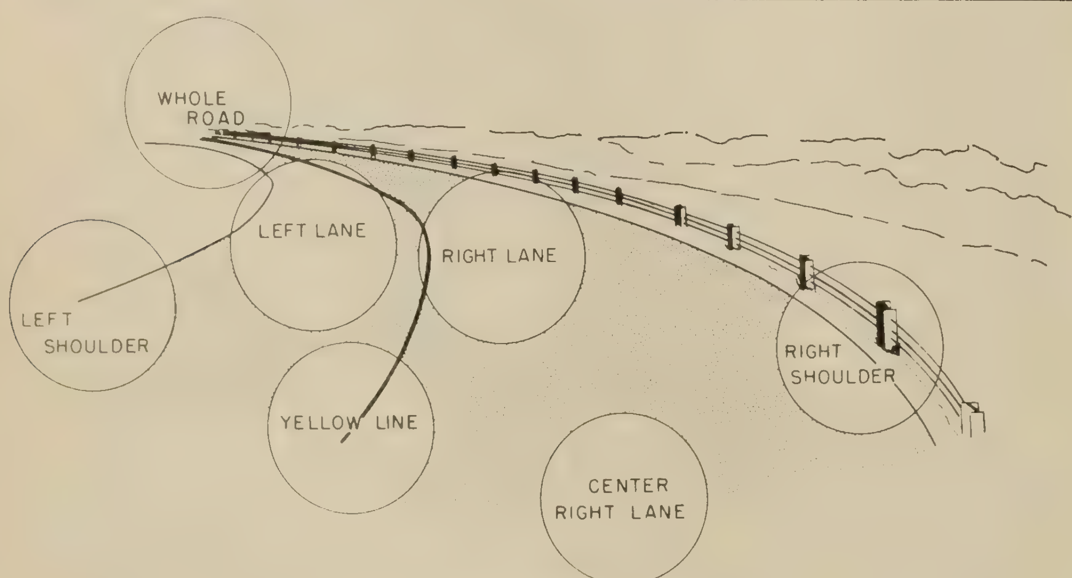

Figure 4.—Sample fixation areas.

singly. A few of the fixations were coded as "center of the left lane" or "center of the right lane." These areas did not include an edge or the centerline.

Fixation position designated the center of the fixation circle, which usually fell on the left shoulder, yellow line, right shoulder, or center of the right or left lane. Distance from the driver's eye was determined by noting on the film editor the width of the road at the center of aim. This width could then be compared with the precalibrated road widths at 50, 100, and 150 feet from the camera. The fixations could be classified as less than 50 feet, 50 to 100 feet, 100 to 150 feet, or more than 150 feet.

Essential Information Used by Driver

On the basis of the drivers' fixations, the road edges and the centerline are the essential information a driver needs. The importance of these features is shown by the summary results of fixation area and position given in tables 1 and 2. It is significant that 96.4 percent of small-aperture viewing and 99.8 percent of large-aperture viewing included an edge or center of the road. Fixation times coded under other areas may not have included an edge or the center.

The fixation position data given in table 2 confirm the importance of edge and centerline information; 80.9 percent of the large-aperture fixations and 85.7 percent of the small-aperture fixations were on edges or the centerline. Fixations not on these features included center of right lane, center of left lane, and trees on left and right. Considering the legitimate demands on a driver's attention of signs and passing cars, it is noteworthy that so high a proportion of fixations was centered on the road and edge borders.

The road edges and centerline also were referred to in the taped verbal statements made by the drivers while on the test route; these replies are summarized in table 3. Statements such as: "now my eye is on the yellow line," or "now my eye is on the right shoulder . . . near, etc." were coded as referring to the road. Such statements as "my vision just shifted back out where the sign is on the curve," or "there is an electric pole in front of us" were coded as not referring to the road. As illustrated, 96.3 percent of the comments made when the small aperture was used, 95.5 percent of the comments made when the large aperture was used, and 84.2 percent of the comments made when no aperture was used, referred to the road. The answers to the questions asked at the conclusion of each run support the conclusion that road edges and the centerline are the important fixation points for a driver. Each of the 10 drivers stated that he used the yellow line, and 9 of the 10 mentioned the right shoulder at least once during the trials. Their other comments referred mainly to anticipation and alinement, which are discussed later.

The finding that the driver depends upon road edges and the centerline for guidance has a number of implications for highway research. One is the desirability of marking the highway edges. Poor contrast of the road edge will affect the safety of the driver and the movement of traffic, particularly at night or in fog. These findings tend to support some of the theories on lateral guidance. One of the theories supported is that steering a car involves the maintenance of an acceptable, steady-state visual condition and the nulling of deviations from an acceptable state. The theory that the visual feedback for steering is slewing and sideslipping movements of road boundaries is also supported. However, the findings of the study reported here do not themselves prove these theories to be correct. The findings also imply the direction future research in this area might follow. Visibility studies should be undertaken of road edges and centerlines under night and fog conditions. The penalty of adverse visibility conditions and the advantages of using highway markings, reflectors, luminaires, and other devices should be assessed. The visibility of lane and edge markings can be assessed by using available formulas for luminance, size, and background contrast (*5*).

Table 1.—Time in seconds on different fixation areas—10 drivers, combined left and right curves

Distance, eye to fixation	Time of fixation in fixation areas											
	Left lane		Yellow line		Right lane		Whole road		Other areas		Total	
LARGE APERTURE												
Feet	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*
150 or more	51.82	4.30	2.58	0.21	140.84	11.70	486.42	40.38	------	------	681.66	56.59
100–150	26.58	2.20	3.08	0.26	53.41	4.43	156.77	13.02	------	------	239.84	19.91
50–100	12.98	1.08	4.41	0.37	63.02	5.23	155.07	12.87	1.00	0.08	236.48	19.63
Less than 50	3.45	0.29	5.60	0.46	12.15	1.01	24.56	2.04	0.82	0.07	46.58	3.87
Total	94.84	7.87	15.67	1.30	269.42	22.37	822.82	68.31	1.82	0.15	1,204.56	100.00
SMALL APERTURE												
150 or more	179.22	14.27	75.21	5.99	355.49	28.31	197.09	15.70	19.23	1.53	826.24	65.80
100–150	25.32	2.02	46.60	3.71	97.87	7.80	33.13	2.64	13.13	1.04	216.05	17.21
50–100	8.67	0.69	52.91	4.21	102.65	8.17	11.38	0.91	11.04	0.88	186.65	14.86
Less than 50	0.86	0.07	8.41	0.67	14.31	1.14	1.34	0.10	1.85	0.15	26.77	2.13
Total	214.07	17.05	183.13	14.58	570.32	45.42	242.94	19.35	45.25	3.60	1,255.71	100.00

Table 3.—On-route identification of fixation positions—10 drivers

Test drivers	Statements identifying fixation positions					
	Open viewing		Large aperture		Small aperture	
	Number	References to road	Number	References to road	Number	References to road
E. C.	7	4	13	10	9	7
G. W.	28	26	15	14	11	11
D. C.	11	6	13	13	9	9
G. R.	23	22	34	34	38	38
L. H.	3	3	9	9	15	15
S. B.	33	33	65	65	58	58
G. P.	16	14	11	11	22	20
R. O'C.	37	32	60	59	105	103
B. C.	18	14	30	24	30	27
F. T.	11	9	15	14	25	22
Total	187	163	265	253	322	310
References to road (pct.)	87.2		95.5		96.3	

Forward Reference Distance

Although all drivers guided the vehicle by reference to the road edges and the centerline, the manner in which information was obtained differed. The variation in approach is clearly illustrated in individual records given in tables 4–6. Driver G. P. tended to view the yellow centerline at a distance beyond 150 feet, thus including the yellow line or right lane in the field of view of the small aperture and the entire road in the large aperture. Driver G. W. looked mainly at the right shoulder. Driver R. O'C. shifted fixations between the centerline and the right shoulder. His main center of viewing was beyond 150 feet. These records refute the belief that a common sequence of viewing is shared by all drivers.

It has been proposed that the driver has a fixed forward fixation distance, which increases with vehicular speed (*6*). If the driver did not look ahead to compensate for man-vehicle reaction, he could not meet the current situation. Forward reference distance should increase with vehicular speed to compensate for increased stopping time.

To test the validity of the forward reference formulation, correlations were computed on the 10 test drivers between speed and average forward reference distance. Driver speed was obtained by determining the film time between known points on the course. Distance divided by time then indicated rate. The average forward reference distance was obtained by averaging fixation distances. Separate figures were obtained on the drivers who started at each of the two ends of the course. Correlations of forward reference position with speed, when the small aperture was used, were 0.55 and −0.37 and when the large aperture was used they were −0.52 and 0.15 ($N=5$). These results indicate no systematic relation between average forward reference distance and vehicular speed. The average fixation distance of 142 feet, which was the same for both apertures, seems to be longer than required to respond at average speeds of 13.4 m.p.h. for the small aperture or 14.7 m.p.h. for the large aperture. Even if a relation had existed between average forward reference distance and speed, it would not be very meaningful because of the variability of the fixation positions. The driver ordinarily looks far ahead of the car and then, seemingly in disregard of anticipation requirements, he may check his alinement with the road. This variability and the adjustment of fixation to particular road conditions makes the concept of average forward reference distance largely an abstraction.

Table 2.—Time in seconds on different fixation positions—10 drivers, combined left and right curves

Distance, eye to fixation	Time of fixation on fixation points													
	Left shoulder		Yellow line		Right shoulder		Center right lane		Center left lane		Trees left and right		Total	
LARGE APERTURE														
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	150.28	12.47	129.19	10.72	340.89	28.30	44.15	3.67	10.19	0.85	6.96	0.58	681.66	56.59
100–150	37.82	3.14	58.49	4.86	83.81	6.96	41.37	3.43	18.16	1.50	0.19	0.02	239.84	19.91
50–100	12.01	1.00	49.06	4.07	85.28	7.08	83.90	6.96	6.22	0.52	-----	----	236.48	19.63
Less than 50	-----	----	12.53	1.04	15.28	1.27	18.59	1.54	0.19	0.02	-----	----	46.58	3.87
Total	200.11	16.61	249.27	20.69	525.26	43.61	188.01	15.60	34.76	2.89	7.15	0.60	1,204.56	100.00
SMALL APERTURE														
150 or more	104.49	8.32	357.60	28.48	252.88	20.14	87.41	6.96	10.71	0.85	13.15	1.05	826.24	65.80
100–150	18.50	1.47	80.34	6.40	77.80	6.20	34.04	2.71	5.37	0.43	-----	----	216.05	17.21
50–100	2.72	0.22	79.91	6.36	79.11	6.30	21.65	1.72	3.26	0.26	-----	----	186.65	14.86
Less than 50	0.33	0.03	12.53	1.00	10.39	0.82	2.93	0.23	0.59	0.05	-----	----	26.77	2.13
Total	126.04	10.04	530.38	42.24	420.18	33.46	146.03	11.62	19.93	1.59	13.15	1.05	1,255.71	100.00

Left and Right Curves

The fixation pattern differed somewhat on left and right curves, as shown in tables 7, 8, 9, and 10. The point of fixation in distant vision deserves special attention. Signs and other visual aids should presumably be located where the motorists eye tends to fall. When drivers looked through the large aperture, their eye fell 6.48 feet from the right edge of the road (left curve average of fixations beyond 150 feet). The corresponding figure for the right curve was 8.91 feet. When the small aperture was used, the drivers' eyes fell 6.95 feet from the right edge on a left curve and 10.38 feet on a right curve. The average shifts in fixation position are statistically significant at the 0.01 level (*t*-test). Apparently the eye moves to the left on a right curve; but on the average, it does not cross into the opposing lane. The results support the practice of placement of signs on the right side of the road.

Perceptual Anticipation and Alinement

Most records show continuous visual shifts, forward to the limit of the road and backward toward the vehicle. The record of driver E. C. shown in figure 5 illustrates these movements. On the left curve, rapid fixation movements occurred between positions beyond 150 feet and those less than 50 feet from the driver. These shifts also occurred along the right shoulder when the driver was on a right curve. When the small aperture was used, 48 percent of all drivers' fixation sequences crossed the zone borders at 50, 100, or 150 feet, and when the large aperture was used, 55 percent of the drivers' sequences crossed the zone borders at these distances. These movements may be explained by the con-

Table 4, Part 1.—Time in seconds required by driver G. P. on different fixation areas and positions through small aperture—left curve

Distance, eye to fixation	Time required for fixation area														Time required for fixation position							
	Left lane		Yellow line		Right lane		Whole road		Left shoulder		Right shoulder		Total		Left shoulder		Yellow line		Right shoulder		Total	
	LEFT CURVE, SMALL APERTURE														LEFT CURVE, SMALL APERTURE							
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	35.47	23.9	37.73	25.5	18.61	12.6	38.26	25.8	7.12	4.8	2.63	1.8	139.82	94.4	3.26	2.2	124.11	83.8	12.45	8.4	139.82	94.4
100-150	---	---	4.67	3.1	---	---	---	---	---	---	---	---	4.67	3.1	---	---	4.67	3.1	---	---	4.67	3.1
50-100	---	---	2.45	1.6	---	---	0.70	0.5	---	---	0.11	0.1	---	---	---	---	3.15	2.1	0.11	0.1	3.26	2.2
Less than 50	---	---	0.41	0.3	---	---	---	---	---	---	---	---	0.41	0.3	---	---	0.41	0.3	---	---	0.41	0.3
Total	35.47	23.9	45.26	30.5	18.61	12.6	38.96	26.3	.12	4.8	2.74	1.9	148.16	100.0	3.26	2.2	132.34	89.3	12.56	8.5	148.16	100.0

Table 4, Part 2.—Time in seconds required by driver G. P. on different fixation areas and positions through large aperture—right curve

Distance, eye to fixation	Time required for fixation area						Time required for fixation position									
	Yellow line		Whole road		Total		Left shoulder		Yellow line		Right shoulder		Trees		Total	
	RIGHT CURVE, LARGE APERTURE						RIGHT CURVE, LARGE APERTURE									
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	0.82	0.7	111.43	93.3	112.25	94.0	27.69	23.2	39.60	33.2	43.74	36.6	1.22	1.0	112.25	94.0
100-150	0.89	0.8	4.67	3.9	5.56	4.7	0.74	0.6	3.22	2.7	1.60	1.4	------	-----	5.56	4.7
50-100	-----	-----	1.19	1.0	1.19	1.0	------	-----	1.19	1.0	------	-----	------	-----	1.19	1.0
Less than 50	-----	-----	0.37	0.3	0.37	0.3	------	-----	0.37	0.3	------	-----	------	-----	0.37	0.3
Total	1.71	1.5	117.66	98.5	119.37	100.0	28.43	23.8	44.38	37.2	45.34	38.0	1.22	1.0	119.37	100.0

tradictory requirements of perceptual anticipation and vehicular alinement. Perceptual anticipation requires the driver to look far ahead to obtain a general idea of conditions that will have to be met. Alinement behavior requires closeup viewing to ensure that the vehicle is on the road.

The drivers mentioned anticipation and alinement in explaining how they guided the car. Excerpts from the record illustrate these activities:

Question: How did you guide yourself on the right curve.

Table 5.—Time in seconds used by driver G. W. on different fixation areas and positions—combined left and right curves

Distance, eye to fixation	Time of fixation															
	Fixation area						Fixation position									
	Right lane		Whole road		Total		Left shoulder		Yellow line		Right shoulder		Center right lane		Total	
	SMALL APERTURE															
	Seconds	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*	*Seconds*	*Percent*
150 or more	8.23	8.4	7.12	7.2	15.35	15.6	0.41	0.4	2.74	2.8	12.20	12.4	-----	-----	15.35	15.6
100-150	30.40	30.8	3.15	3.2	33.55	34.0	-----	-----	0.26	0.2	32.92	33.4	0.37	0.4	33.55	34.0
50-100	47.15	47.9	0.11	0.1	47.26	48.0	-----	-----	0.11	0.1	47.15	47.9	-----	-----	47.26	48.0
Less than 50	2.37	2.4	-----	-----	2.37	2.4	-----	-----	-----	-----	2.37	2.4	-----	-----	2.37	2.4
Total	88.15	89.5	10.38	10.5	98.53	100.0	0.41	0.4	3.11	3.1	94.64	96.1	0.37	0.4	98.53	100.0
	LARGE APERTURE															
150 or more	32.66	30.8	64.20	60.7	96.86	91.5	13.72	13.0	6.86	6.5	72.65	68.6	3.63	3.4	96.86	91.5
100-150	7.34	7.0	0.56	0.5	7.90	7.5	-----	-----	-----	-----	7.90	7.5	-----	-----	7.90	7.5
50-100	0.52	0.5	0.52	0.5	1.04	1.0	-----	-----	0.52	0.5	0.52	0.5	-----	-----	1.04	1.0
Less than 50	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Total	40.52	38.3	65.28	61.7	105.80	100.0	13.72	13.0	7.38	7.0	81.07	76.6	3.63	3.4	105.80	100.0

Table 6.—Time in seconds used by driver R. O'C. on different fixation areas and positions—combined left and right curves

Distance, eye to fixation	Time of fixation																					
	Fixation area										Fixation position											
	Left lane		Yellow line		Right lane		Whole road		Total		Left shoulder		Yellow line		Right shoulder		Center right lane		Center left lane		Total	
	SMALL APERTURE																					
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	53.45	31.5	10.94	6.4	56.64	33.3	31.17	18.4	152.20	89.6	22.28	13.1	57.90	34.1	42.00	24.7	28.20	16.6	1.82	1.1	152.20	89.6
100-150	1.74	1.0	2.19	1.3	13.16	7.7	-----	----	17.09	10.0	0.07	0.0	4.82	2.8	9.68	5.7	2.52	1.5	----	----	17.09	10.0
50-100	-----	-----	-----	----	0.63	0.4	-----	----	0.63	0.4	-----	----	-----	----	0.63	0.4	-----	----	----	----	0.63	0.4
Less than 50	-----	-----	-----	----	-----	----	-----	----	------	-----	-----	----	-----	----	-----	----	-----	----	----	----	------	------
Total	55.19	32.5	13.13	7.7	70.43	41.4	31.17	18.4	169.92	100.0	22.35	13.1	62.72	36.9	52.31	30.8	30.72	18.1	1.82	1.1	169.92	100.0
	LARGE APERTURE																					
150 or more	NA	NA	NA	NA	20.80	16.2	79.39	56.1	93.19	72.3	18.61	14.4	12.49	9.7	60.20	46.7	1.89	1.5	NA	NA	93.19	72.3
100-150	NA	NA	NA	NA	7.12	5.5	27.58	21.4	34.70	26.9	4.97	3.9	5.56	4.3	21.09	16.3	3.08	2.4	NA	NA	34.70	26.9
50-100	NA	NA	NA	NA	1.07	0.8	-----	----	1.07	9.8	-----	----	-----	----	0.18	0.1	0.89	0.7	NA	NA	1.07	0.8
Less than 50	NA	NA	NA	NA	-----	----	-----	----	------	-----	-----	----	-----	----	-----	----	-----	----	NA	NA	------	------
Total	NA	NA	NA	NA	28.99	22.5	99.97	77.5	127.96	100.0	23.58	18.3	18.05	14.0	81.47	63.1	5.86	4.6	NA	NA	128.96	100.0

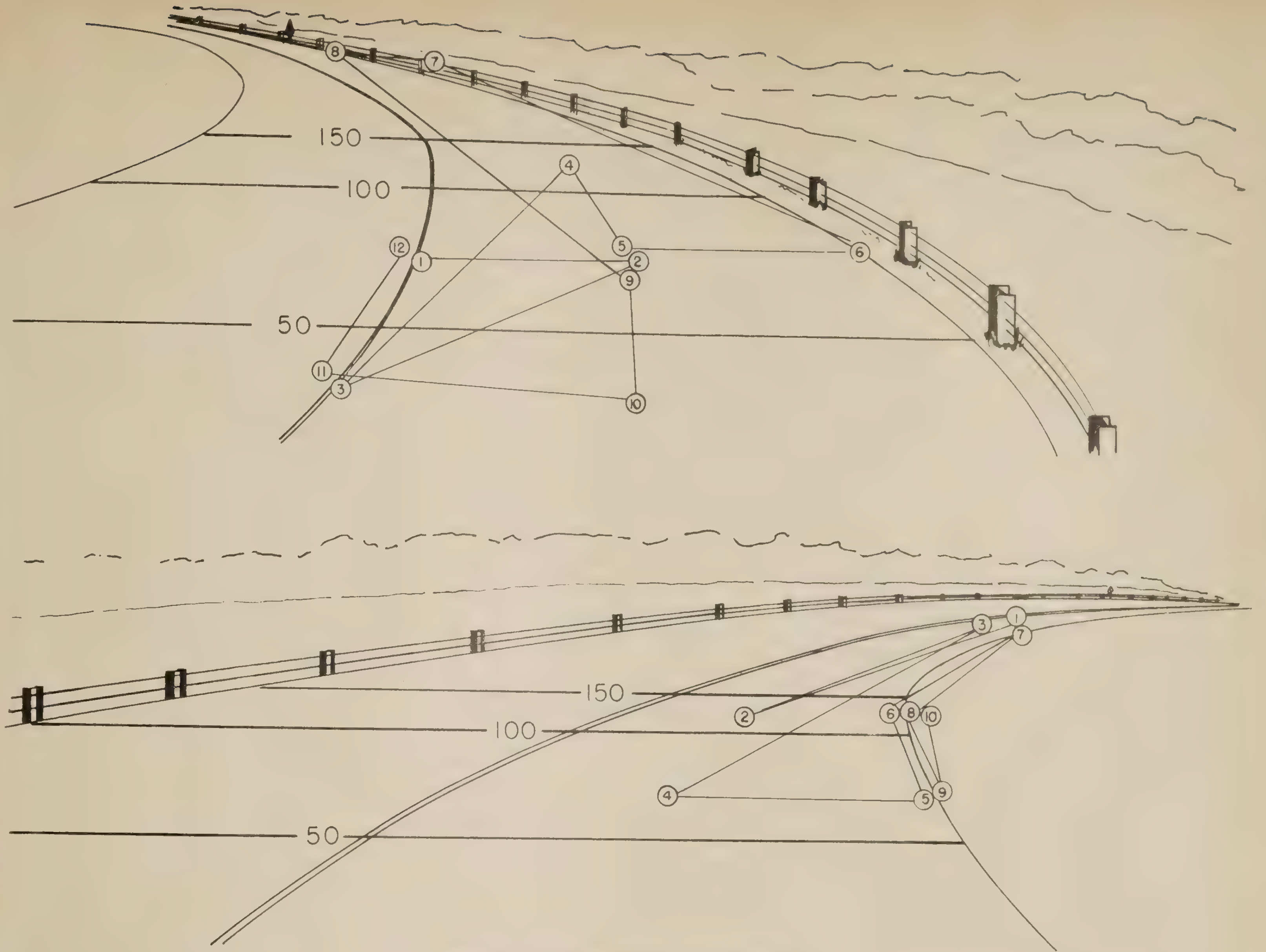

Figure 5.—Anticipation and alinement.

Answer by test driver G. P. when small aperture was used: "Well, I just saw the same thing. My vision would go out to the curve. I'd see as much as I could and then come back again. One time I stayed out too long and I was out of the road."

Question: Was there any pattern of movement.

Answer by test driver R. O'C. when small aperture was used: "Just that I . . . you look ahead frequently to see the whole situation—then come back to your immediate points of reference. I wanted to see what was ahead and then put myself within the lane by something closer—centerline or shoulder line."

Question: How did you guide yourself on the left curve.

Answer by test driver N. M. when no aperture limitations were imposed: "Going into a left turn, generally I was looking at the center strip and the curvature in the distance along the left side of the road. And as I approached the curve—got into the curve—I was looking generally at the center strip and the right side of the shoulder."

The author recommends that the driver should always be given an unimpeded view ahead that is sufficient to satisfy his anticipation requirements. The fact that drivers need to perceptually anticipate conditions ahead has application to road design. This need to anticipate conditions ahead has been recognized in traffic regulation and guidance, road design manuals, and comes out clearly in the data collected in the study reported here. Little is known about perceptual anticipation requirements in the variety of situations met on the highway and further research in this area may be very profitable.

Methodological Problems

Two of the methodological problems encountered in the study discussed here are: (1) The adequacy of introspective data (on-route

Table 7.—Summary of time required by 10 drivers, using aperture, on different fixation positions

Distance, eye to fixation	Time required for fixation													
	Left shoulder		Yellow line		Right shoulder		Center right lane		Center left lane		Trees, left and right sides		Total	
LEFT CURVE														
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	49.86	7.91	88.34	14.02	192.06	30.50	19.05	3.03	8.63	1.37	6.59	1.04	364.53	57.87
100–150	14.68	2.33	37.66	5.98	47.89	7.60	25.02	3.97	17.05	2.71	0.19	0.03	142.49	22.62
50–100	6.79	1.08	35.45	5.63	15.89	2.52	42.22	6.70	4.52	0.72	----	----	104.87	16.65
Less than 50	-----	----	9.82	1.56	1.45	0.23	6.56	1.04	0.19	0.03	----	----	18.02	2.86
Total	71.33	11.32	171.27	27.19	257.29	40.85	92.85	14.74	30.39	4.83	6.78	1.07	629.91	100.00
RIGHT CURVE														
150 or more	100.42	17.47	40.85	7.11	148.83	25.90	25.10	4.37	1.56	0.27	0.37	0.07	317.13	55.19
100–150	23.14	4.03	20.83	3.62	35.92	6.62	16.35	2.85	1.11	0.19	---	--	97.35	16.94
50–100	5.22	0.91	13.61	2.37	69.39	12.07	41.68	7.25	1.70	0.30	----	----	131.60	22.90
Less than 50	-----	----	2.71	0.47	13.83	2.41	12.03	2.09	----	----	----	----	28.57	4.97
Total	128.78	22.41	78.00	13.57	267.97	46.63	95.16	16.56	4.37	0.76	0.37	0.07	574.65	100.00

statements of fixation, answers to questionnaires) for indicating the driver's visual input, and (2) the effects of the stress imposed by limiting information with the small aperture. The on-route statements and the questionnaire data were suggestive, but the introspective data had a shortcoming of incompleteness. The 3,305 separate film fixations obtained permitted a reliable analysis of the distribution and sequence of eye positionings. In contrast, the 563 statements given on-route and the 20 questionnaire responses offered only a skeletal indication of what was going on. However, the introspective data provided confirming evidence of the validity of the film analysis, and they were valuable in revealing the drivers' purposes in perceptual anticipation and alinement. These uses and limitations of introspective data are similar to those generally encountered in experimental work. The complexity of fixation data has been noted in previous eye camera studies (7).

The adaptation made by drivers to the stress of limited information is shown by a comparison of results from tests in which the small and large apertures were used (tables 1 and 2). When looking through the small aperture, drivers fixated the yellow line 42.4 percent of the time and the right shoulder 33.5 percent, and this enabled them to track the yellow line or view the entire right lane. When looking through the large aperture, drivers could see the entire road and this inclusive feature was used 68.3 percent of the time; the right lane was used 22.4 percent of the time as it could be covered even when the driver looked close to the car. The records seem to indicate that the driver selects a view that permits him to do the job. Under stress, this may be as simple as holding fast to the yellow line and tracking it, as illustrated by the record of G. P. given in table 4. However, the driver prefers to see more of the road; even when the small aperture was used, the entire right lane was viewed 45.4 percent of the time and the entire road 19.4 percent of the time.

Recommendations

The experimental evidence of the study reported here is the basis of suggestions for the design of highway markings. The experimental evidence must be weighed along with considerations of cost, public acceptance, current usage, and similar factors before it can be applied. But experimental findings have special status because they are perhaps less subject to debate than other considerations.

Results of the study provide a rationalization for edge and center lane markings. The question remains as to which features should be emphasized by being specially marked. The evidence indicates that driving can be done by use of only the centerline (table 1, small aperture). This might lead to the recommendation that only the centerline be presented. However, drivers prefer to see the right lane and the entire road, as evidenced by the large proportion of total time spent on these features. Factors other than those considered in the experiment reported in this article will dictate road marking policy. For example, road edges differ in luminance and contrast, and hence the need for them to be painted. Where contrast is low or where night usage is heavy, edge markings are recommended. Where two-way traffic is heavy, a centerline should be used.

The analysis of fixations on curves indicates that a driver tends to shift his distance fixation to the left on a right curve. However, the movement is not large enough to move the average fixation position across into the opposing lane. Presumably then, highway markings should be presented on the right side of the road.

Table 8.—Summary of time required by 10 drivers, using large aperture, on different fixation areas

Distance, eye to fixation	Time required for fixation											
	Left lane		Yellow line		Right lane		Whole road		Other areas [1]		Total	
LEFT CURVE												
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	5.41	0.85	2.58	0.41	135.72	21.55	220.82	35.06	----	----	364.53	57.87
100–150	6.52	1.04	3.08	0.49	53.41	8.48	79.48	12.61	----	----	142.49	22.62
50–100	3.60	0.57	4.41	0.70	52.42	8.32	43.44	6.90	1.00	0.16	104.87	16.65
Less than 50	1.19	0.19	5.23	0.83	6.67	1.06	4.11	0.65	0.82	0.13	18.02	2.86
Total	16.72	2.65	15.30	2.43	248.22	39.41	347.85	55.22	1.82	0.29	629.91	100.00
RIGHT CURVE												
150 or more	46.41	8.08	----	----	5.12	0.89	265.60	46.22	NA	NA	317.13	55.19
100–150	20.06	3.49	----	----	-----	----	77.29	13.45	NA	NA	97.35	16.94
50–100	9.38	1.63	----	----	10.60	1.85	111.63	19.42	NA	NA	131.60	22.90
Less than 50	2.26	0.39	0.37	0.07	5.48	0.95	20.45	3.56	NA	NA	28.57	4.97
Total	78.11	13.59	0.37	0.07	21.20	3.69	474.97	82.65	NA	NA	574.65	100.00

[1] Left shoulder, center left lane, center right lane, right shoulder.

Table 9.—Summary of time in seconds required by 10 drivers, using small aperture, on different fixation positions

Distance, eye to fixation	Time required for fixation													
	Left shoulder		Yellow line		Right shoulder		Center right lane		Center left lane		Trees, left and right		Total	
LEFT CURVE														
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	33.40	4.50	174.56	23.50	176.97	23.83	56.08	7.55	10.71	1.44	11.20	1.51	462.92	62.33
100–150	11.23	1.51	53.56	7.21	35.55	4.79	14.86	2.00	5.38	0.73	----	----	120.58	16.24
50–100	2.37	0.32	64.17	8.64	58.05	7.81	7.71	1.03	3.00	0.40	----	----	135.30	18.20
Less than 50	0.33	0.04	12.34	1.66	8.86	1.19	1.90	0.26	0.59	0.08	----	----	24.02	3.23
Total	47.33	6.37	304.63	41.01	279.43	37.62	80.55	10.84	19.68	2.65	11.20	1.51	742.82	100.00
RIGHT CURVE														
150 or more	71.10	13.87	183.05	35.69	75.92	14.80	31.32	6.11	----	----	1.96	0.38	363.35	70.85
100–150	7.27	1.42	26.76	5.22	42.26	8.24	19.16	3.73	----	----	----	----	95.45	18.61
50–100	0.33	0.06	15.75	3.07	21.06	4.11	13.94	2.72	0.26	0.05	----	----	51.34	10.01
Less than 50	-----	-----	0.19	0.04	1.51	0.29	1.04	0.20	----	----	----	----	2.74	0.53
Total	78.70	15.35	225.75	44.02	140.75	27.44	65.46	12.76	0.26	0.05	1.96	0.38	512.88	100.00

Table 10.—Summary of time in seconds required by 10 drivers, using small aperture, on different fixation areas

Distance, eye to fixation	Time required for fixation											
	Yellow line		Left lane		Whole road		Right lane		Other areas [1]		Total	
LEFT CURVE												
Feet	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*	*Sec.*	*Pct.*
150 or more	53.34	7.18	21.53	2.90	68.84	9.27	310.69	41.83	8.52	1.15	462.92	62.33
100–150	37.03	5.00	6.64	0.89	12.93	1.74	56.00	7.54	7.98	1.07	120.58	16.24
50–100	43.19	5.80	2.70	0.36	6.82	0.92	77.59	10.45	5.00	0.67	135.30	18.20
Less than 50	8.41	1.13	0.86	0.12	1.15	0.15	12.79	1.72	0.81	0.11	24.02	3.23
Total	141.97	19.11	31.73	4.27	89.74	12.08	457.07	61.54	22.31	3.00	742.82	100.00
RIGHT CURVE												
150 or more	21.87	4.26	157.70	30.75	128.25	25.01	44.82	8.74	10.71	2.09	363.35	70.85
100–150	9.57	1.87	18.68	3.64	20.20	3.94	41.85	8.16	5.15	1.00	95.45	18.61
50–100	9.72	1.90	5.96	1.16	4.56	0.88	25.06	4.89	6.04	1.18	51.34	10.01
Less than 50	------	------	------	------	0.18	0.04	1.52	0.29	1.04	0.20	2.74	0.53
Total	41.16	8.03	182.34	35.55	153.19	29.87	113.25	22.08	22.94	4.47	512.88	100.00

[1] Right shoulders, left shoulders, center right lane, center left lane.

Summary and Conclusions

A technique to determine what features of the road and terrain the driver is responding to is presented in this article. The method involved having the driver guide the car while looking through a device containing a small aperture. By decreasing the visual field, the essential information, whatever it is, cannot be seen at once: the driver is forced to obtain this information in separate visual fixations. A continuous film record was made of the driver's field of view and later analyzed to indicate the center of his visual aim and the content of each fixation. This aperture device was used to obtain visual positional data on 10 drivers who followed a 2-lane road, where traffic density was low. The film records provided 3,305 separate fixations, which were coded for position, distance from the eye, and duration. Conclusions made on the basis of the analysis were:

- The essential information required by a driver is provided by the road edges and center lane marker. At least one of these road features was included in 98.2 percent of the fixations made when the large aperture was used. The drivers' on-route statements of fixation position, and the answers to a questionnaire also indicated the importance of the road edges and lane marker.
- Although all drivers utilize the road edges and centerline to guide the vehicle, the manner in which this information is obtained differs from subject to subject. The film records refuted the idea that the driver has a fixed point of forward reference or that a common pattern of viewing is shared by all drivers.
- In going from a left to a right curve, the position of fixation tends to shift in the opposite direction, that is from right to left. However, the average point of fixation beyond 150 feet did not cross the centerline into the opposing lane.
- The persistent pattern of fixation movements, forward to the limits of the road and back again to the vehicle, are explained by the contradictory requirements of perceptual anticipation and vehicular alinement with the road. This conclusion and the preceding one should be tested further, if possible, with eye-camera techniques.

Methodological problems concerning the adequacy of introspective data for determining the driver's visual input, and the stress of small-aperture viewing have been discussed. The implications of results to the placement of signs and highway markings have been presented.

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Travel Habits in Cities of 100,000 or More

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

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The preferences for certain modes of transportation by the urban population are considered in the survey reported in this article. These preferences are expected to be helpful in planning for highways and transportation systems to meet the needs of an expected urban population of 230 million by 1990.

Travel habits, income, and other information about the economics of persons living in cities of 100,000 or more population are discussed. Information is included on the availability of the nearest public transportation to work and the mode of travel to work; the relationship between family income and the mode of travel to work; and the distribution of automobile trips and travel to the downtown shopping areas, by purpose and length of trip.

During the spring of 1961, a nationwide automobile-use survey was made for the Bureau of Public Roads by the Bureau of the Census. In addition to the characteristics of automobile use by households, data were collected on income and composition of families for different population groupings. Because it has been estimated that 80 percent of the people in the United States will be living in urban areas by 1990, the preferences for certain modes of transportation and of how these preferences may influence the direction of future transportation development must be considered in current planning.

Introduction

THE PURPOSE of this article is to present some information on the travel characteristics of workers now living in cities, exclusive of the surrounding urban areas, where the population is 100,000 or more. The data considered are the choice of travel modes used by workers related to the nearness of public transportation to work, the distance to work, and the family income. Also considered is the distribution of trips and travel to the downtown area by purpose of trips and, for each purpose, the proportion of all trips destined for the downtown area.

The principal data on which this article is based were derived from a nationwide automobile-use survey conducted in the spring of 1961 by the Bureau of the Census under contract to the Bureau of Public Roads, supplemented by information that since has become available. The sample used by the Bureau of the Census was approximately 5,000 dwelling units from the Current Population Survey. This survey, conducted monthly by the Bureau of the Census, is based on a statistically selected sample representing the noninstitutional civilian poplation. It is made to obtain current information on employment, unemployment, and related economics. Data from more than 1,300 of the 5,000 households in the sample were collected for the study reported in this article. These households were located in cities having a population of 100,000 or more. Because these data were based on a probability sampling of households, the information is subject to sampling variability.

The term "sampling variability" refers to the differences that might be expected between results of sample surveys and the results that would have been obtained from a complete enumeration of all households. Based on the estimates of sampling variability that occurred as a result of the use of the sample of 1,300, the odds were about 2 to 1 that the estimated number of trips would differ by no more than 10 percent from the unknown value that would have been obtained had the complete enumeration been made. The comparable measure of relative sampling variability for the estimate of vehicle miles was 20 percent for the same odds.

Conclusions

Information related to travel characteristics of residents of large cities, obtained from sources that are valid for nationwide (but not local) comparisons, has been presented in this article. From this information, it is concluded that the automobile is the mode of transportation used by a large proportion of the residents of large cities, regardless of the availability of other modes. Because a worker lives close to public transportation does not necessarily influence his use of it as his regular means of getting to and from work. Neither does closeness of home to work by itself prompt a worker to forego use of his automobile for trips to work. Use of the automobile for trips to work tends to increase as income increases.

Although only one-seventh of all automobile trips made for purposes of earning a living were destined for the downtown area, more than half of all the trips having downtown destinations were made for this purpose.

Background

An assumption can be made that the major portion of highway needs of this country will be concentrated in urban areas in the next two or three decades. Probably by 1990 about 80 percent of the total population of the 48 contiguous States and the District of Columbia will be residing in urban areas. Projections of future population range from 262 million to 301 million for the year 1990. A recent projection prepared by the Bureau of Public Roads for 1990 is 286 million. If the probability holds that 80 percent would be residents of urban areas, the resultant urban population would be 230 million.

The planning and constructing of the urban highway system—or, for that matter, systems including all modes of urban transportation—to meet the travel needs and desires of 230 million persons is a task of unparalleled magnitude in transportation history. As more and more people live in urban concentrations, planning for transportation systems becomes increasingly necessary. Such systems should embrace the different modes of transportation in a balance that will provide efficient and effective service for States and local communities. The study of travel habits of workers reported here provides some information on preferences for certain modes of transportation and how these preferences may suggest the trend of future transportation development.

Transportation to Work

Some form of public transportation was available within 2 blocks of the homes of 69.3 percent of all workers who lived in places having a population of 100,000 or more, as shown in table 1. At the other extreme, 8 percent had no public transportation available for trips to work. Public transportation was available 6 blocks or less from home for 87 percent of all workers. Furthermore, of the workers living 15 miles or more from work, 15.6 percent had no public transportation available nearer than 6 blocks or less from home; for workers living closer than 15 miles to work, less than 5 percent had no public transportation closer than 6 blocks from their homes.

Half of all workers who had some form of public transportation available for trips to work chose to use automobiles for this purpose, as shown in table 2. The percentage was a little more than the average for workers who lived within 2 blocks of public transportation. Possible reasons for this might have been inadequacy of or dissatisfaction with the public transportation system.

The time factor may have entered into the choice of the automobile as the means of getting to work. The Bureau of the Census has compiled data in the Preliminary Progress Report, Home to Work Travel Survey, 1963 Census of Transportation. In the data shown

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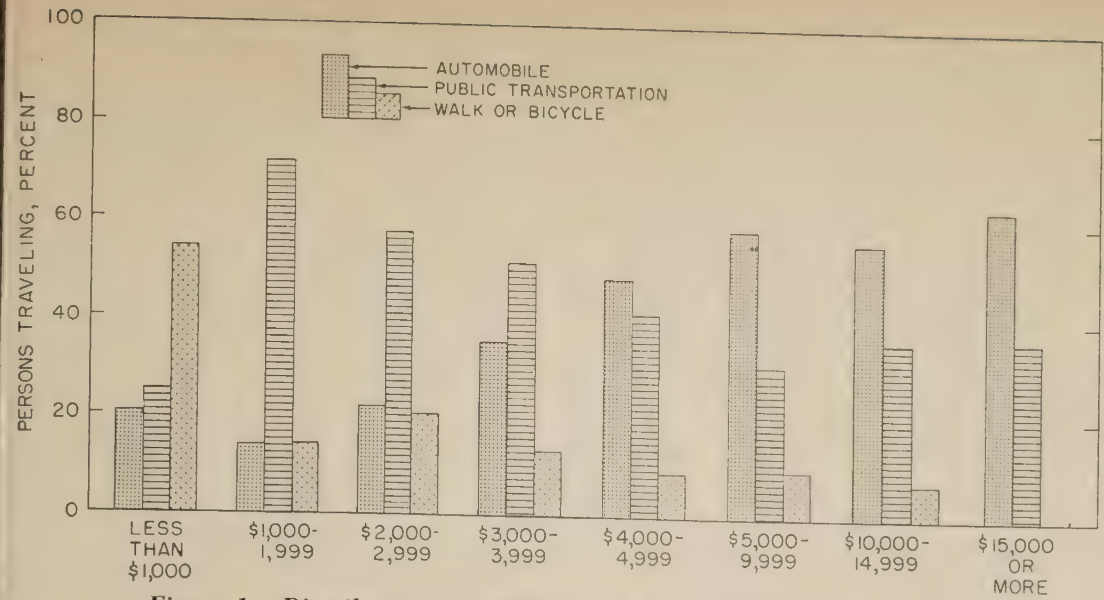

Figure 1.—Distribution of persons in each family group, by mode of home-to-work transportation.

for central cities of standard metropolitan statistical areas, 74 percent of the persons commuting to work by automobile required less than 25 minutes to get there, whereas only 25 percent of the workers commuting by public transportation were able to get to work within that time. These figures may be an indication of the importance that commuters attach to time savings.

Of the one-half of all workers who did not choose to go to work by automobile, 38.6 percent used public transportation and 11.5 percent walked or used a bicycle, as shown in table 3. Where the distance to work was less than 1 mile, 74.9 percent of the workers either walked or rode a bicycle. But even at this relatively short distance from home to work, 14 percent chose to go by automobile and 11.1 percent used public transportation. Moreover, most of those who went by automobile were drivers, not passengers.

The mode of travel to work, by 1-mile increments from 1 to 4.9 miles and then by 5-mile increments, is shown in table 3. Generally, the longer the distance from work, the larger the proportion was of workers using automobiles for home-to-work transportation. Data in the table also indicate that mileage to work influences the extent of car pooling. As the distance to work increased to more than 3 miles, a higher proportion of workers were reported as automobile passengers, the range being from 5.4 percent in the 4- to 4.9-mileage group to 12.7 percent in the 20- to 24.9-mileage group.

Family Income and Mode of Travel

The choice of mode of travel to work is undoubtedly influenced by many factors, singly or in combination. Probably, at least two and possibly more of these factors enter

Table 1.—Percentage distribution of workers, by distance to nearest public transportation to work [1]

Distance to work, one way	Nearest public transportation, by workers: 1–2 blocks	3–6 blocks	More than 6 blocks	None available
Miles	*Percent*	*Percent*	*Percent*	*Percent*
Less than 5	71.7	15.5	2.8	10.0
5.0–9.9	69.0	23.0	4.7	3.3
10.0–14.9	71.5	19.5	3.0	6.0
15.0 or more	56.2	13.9	15.6	14.3
All distances	69.3	18.0	4.7	8.0

[1] Nationwide automobile-use survey, spring 1961—for persons living in places having a population of 100,000 or more.

Table 2.—Percentage distribution of workers using automobiles for trips to work, by distance to nearest public transportation to work [1]

Distance to work, one way	Nearest public transportation, for workers [2]: 1–2 blocks	3–6 blocks	More than 6 blocks	All distances
Miles	*Percent*	*Percent*	*Percent*	*Percent*
Less than 5	44.8	46.1	56.7	45.4
5.0–9.9	61.2	41.1	39.7	55.3
10.0–14.9	54.3	60.3	51.4	55.4
15.0 or more	53.6	60.3	31.6	50.7
All distances	51.5	47.3	42.8	50.2

[1] Nationwide automobile-use survey, spring 1961—persons living in places having a population of 100,000 or more.
[2] Excludes persons for whom no public transportation was available.

Table 3.—Percentage distribution of workers, by mode of travel and distance to work [1]

Distance to work, one way	Mode of travel, by workers: Automobile: Driver	Automobile: Passenger	Automobile: Total	Public transportation or combination [2]	Walk or bicycle
Miles	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Less than 1	13.1	0.9	14.0	11.1	74.9
1.0–1.9	40.2	4.8	45.0	30.0	25.0
2.0–2.9	41.3	2.1	43.4	51.8	4.8
3.0–3.9	51.0	8.6	59.6	38.7	1.7
4.0–4.9	55.5	5.4	60.9	39.1	(3)
5.0–9.9	48.6	8.5	57.1	42.3	0.6
10.0–14.9	50.5	7.2	57.7	42.3	(3)
15.0–19.9	41.3	8.1	49.4	50.6	(3)
20.0–24.9	52.8	12.7	65.5	34.5	(3)
25.0 or more	55.4	8.6	64.0	36.0	(3)
Unknown [4]	19.7	19.7	39.4	57.4	3.2
Total	43.2	6.7	49.9	38.6	11.5

[1] Nationwide automobile-use study, spring 1961—persons living in places having a population of 100,000 or more.
[2] Public transportation or public transportation and automobile.
[3] Less than 0.1.
[4] Distance not reported, less than 3 percent of that reported.

Table 4.—Percentage distribution of workers, by family income and mode of home-to-work travel [1]

Family income	Mode of travel, by workers: Automobile: Driver	Automobile: Passenger	Automobile: Total	Public transportation or combination [2]	Walk or bicycle
Dollars	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Less than 1,000	15.9	4.7	20.6	25.1	54.3
1,000–1,999	14.1	(3)	14.1	71.7	14.2
2,000–2,999	18.9	3.0	21.9	57.5	20.6
3,000–3,999	26.7	8.5	35.2	51.5	13.3
4,000–4,999	36.6	12.0	48.6	41.4	9.0
5,000–9,999	50.0	9.1	59.1	31.2	9.7
10,000–14,999	54.3	1.9	56.2	36.6	7.2
15,000 or more	63.3	(3)	63.3	36.7	(3)
Unknown [4]	41.7	4.2	45.9	39.8	14.3
Total	43.2	6.7	49.9	38.6	11.5

[1] Nationwide automobile-use study, spring 1961—persons living in places having a population of 100,000 or more.
[2] Public transportation or public transportation and automobile.
[3] Less than 0.1.
[4] Income not reported, 13 percent of sample.

Table 5.—Percentage distribution of automobile trips, by purpose and family income [1]

Purpose of trip	Less than $1,000	$1,000–1,999	$2,000–2,999	$3,000–3,999	$4,000–4,999	$5,000–9,999	$10,000–14,999	$15,000 or more	All income
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Earning a living:									
To and from work	16.2	26.5	30.6	34.9	37.7	36.3	33.8	29.0	34.5
Related business	8.5	1.7	7.2	6.1	4.9	3.5	5.3	4.7	4.4
Total	24.7	28.2	37.8	41.0	42.6	39.8	39.1	33.7	38.9
Family business:									
Medical and dental	3.1	2.1	3.6	1.4	1.2	2.1	1.9	3.4	2.1
Shopping	18.1	23.5	15.2	16.2	13.7	14.1	14.2	17.7	14.9
Other	20.3	18.9	18.5	14.1	14.3	15.0	15.1	12.0	15.1
Total	41.5	44.5	37.3	31.7	29.2	31.2	31.2	33.1	32.1
Educational, civic, and religious	11.6	8.7	11.7	10.4	11.2	12.9	13.1	11.1	12.3
Social and recreational:									
Vacations	(2)	(2)	(2)	(2)	(2)	0.1	(2)	(2)	(2)
Pleasure rides	3.2	2.1	1.6	2.8	2.9	1.9	1.6	3.2	2.1
Other	19.0	16.5	11.6	14.1	14.1	14.1	15.0	18.9	14.6
Total	22.2	18.6	13.2	16.9	17.0	16.1	16.6	22.1	16.7
All purposes	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[1] Nationwide automobile-use study, spring 1961—persons living in places having a population of 100,000 or more.
[2] Less than 0.1.

Table 6.—Percentage distribution of automobile trips and travel to downtown shopping areas, by major purpose [1]

Distance from residence, one way	Purpose of trips and travel							
	Earning a living		Family business		Educational, civic, and religious		Social and recreational	
	Trips	Travel	Trips	Travel	Trips	Travel	Trips	Travel
Miles	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Less than 2	28.6	29.7	62.8	61.7	1.1	0.9	7.5	7.7
2.0–4.9	58.1	57.2	30.3	30.6	2.5	2.6	9.1	9.6
5.0–9.9	51.7	54.5	36.3	34.3	1.7	1.8	10.3	9.4
10.0 or more	50.9	52.5	35.5	34.3	2.2	1.8	11.4	11.4
Total	51.9	53.5	36.3	34.0	2.1	1.9	9.7	10.6

[1] Nationwide automobile-use study, spring 1961—persons living in places having a population of 100,000 or more.

Table 7.—Percentage of all automobile trips, by purpose, to downtown area [1]

Purpose of trip	Percent to downtown business area
Earning a living:	
To and from work	13.7
Related business	20.5
Total	14.5
Family business:	
Medical and dental	13.8
Shopping	13.1
Other	16.6
Total	14.5
Educational, civic, and religious	2.6
Social and recreational	6.7
All purposes	12.0

[1] National automobile-use study, spring 1961—persons living in places having population of 100,000 or more.

into any situation. Income is an important factor both in the choice of methods of going to work and in the distance between the worker's home and his place of employment. As shown in table 4 and figure 1, when family income was less than $1,000, more than half of all workers walked or bicycled to work. Possibly most of this group of families were domiciled at the job site. The data, however, do not show this. Almost 72 percent of the workers in the next income bracket ($1,000 to $1,999) used public transportation—a very substantial shift. The percentage of workers using public transportation dropped rather sharply until family income reached $10,000, at which point it increased somewhat.

As the size of family income increased, the choice of the automobile as a commuting mode increased and 63 percent of the families having incomes of $15,000 or more used automobiles for trips to and from work. Surprisingly, more than 20 percent of the families having the lowest incomes commuted by automobile, more than three-fourths of them driving. The more use of automobiles for home-to-work transportation as the family income exceeded $5,000 may be noted in figure 1, which shows the distribution of persons in each income group according to the mode of home-to-work transportation. Except for the group of families having incomes of less than $1,000, in which 54 percent of the workers reported walking or bicycling to work, the groups were relatively consistent in the proportion of walkers. One might conclude that income above the $1,000 level is not closely related to walking to work.

Purpose of Trips

Family income is generally considered an important determinant in the use of automobiles. The distribution of automobile trips, by purpose, for the different income groups is shown in table 5. The proportion of trips related to earning a living rose from 24.7 percent for the family group having incomes of less than $1,000 to 42.6 percent for the group having incomes of $4,000 to $4,999 and then dropped off steadily to 33.7 percent for the group having incomes of $15,000 or more. Persons in the family groups having incomes of less than $2,000 made a larger proportion of the trips for purposes of family business than persons in other income groups. Social and recreational purposes accounted for 16.7 percent of all trips; groups having the highest and lowest income reported 22 percent of the trips were made for such purposes.

Urban planners are constantly aware of the problems related to keeping traffic flowing to and in central business districts. Although the tremendous buildup of suburban shopping and medical areas has reduced the attraction to a downtown shopping area, the downtown areas still attract people for a variety of reasons. Distribution of trips and travel by automobile to downtown shopping areas is shown in table 6, by purpose of trips. More than half of all trips and travel to the downtown shopping areas was made for purposes of earning a living; an additional one-third of the trips was made on family business. Only 2.1 percent of the trips and 1.9 percent of the travel were made for educational, civic, and religious purposes. Trips made for social and recreational purposes amounted to 9.7 percent of all trips and 10.6 percent of all travel. Persons who lived closer to downtown shopping areas—that is, less than 2 miles—made a smaller proportion of automobile trips to work and a larger proportion on family business than persons living farther from the downtown area.

The percentage of automobile trips to the downtown area, by purpose of the trip, was fairly substantial—12 percent—as shown in table 7. Of all trips related to earning a living, 14.5 percent were made to the downtown area. Trips on family business made to the downtown area also totaled 14.5 percent. Trips made for educational, civic, and religious purposes comprised less than 3 percent of those made to the downtown area; but 6.7 percent of the social and recreational trips were made to the downtown area.

NEW PUBLICATIONS

Highway Progress, 1965

The annual report of the Bureau of Public Roads, U.S. Department of Commerce, *Highway Progress, 1965,* contains a review of the accomplishments of Public Roads on the Federal-aid highway program and its many other activities during the fiscal year 1965. *Highway Progress, 1965,* is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, for 40 cents a copy.

Included in the illustrated publication is a descriptive account of the progress made during fiscal year 1965 in construction of the National System of Interstate and Defense Highways and in improvement of primary highways, secondary roads, and urban arterials under the regular Federal-aid program. Also reported on at length are Public Roads efforts to meet the social responsibilities that face today's highway builder, and its activities and accomplishments in highway planning and design, urban transportation planning, highway beautification, safety, research and development, and management.

The report also describes the highway construction work undertaken directly by the Bureau of Public Roads in national forests and parks and on other Federal lands, and Public Roads activities in providing technical assistance to foreign countries to further the development of their highway organizations and roadbuilding programs. Included in the report's appendix are 19 statistical tables covering the progress and activities of the Federal-aid program during the fiscal year 1965. The data are reported for each State.

U.S. GOVERNMENT PRINTING OFFICE: 1966

PUBLICATIONS
of the Bureau of Public Roads

A list of the more important articles in PUBLIC ROADS *and title sheets for volumes 24–33 are available upon request addressed to Bureau of Public Roads, Washington, D.C., 20235.*

The following publications are sold by the Superintendent of Documents, Government Printing Office, Washington, D.C., 20402. Orders should be sent direct to the Superintendent of Documents. Prepayment is required.

ANNUAL REPORTS

Annual Reports of the Bureau of Public Roads:
1960, 35 cents. 1963, 35 cents. 1964, 35 cents. 1965, 40 cents. (Other years are now out of print.)

REPORTS TO CONGRESS

Federal Role in Highway Safety, House Document No. 93 (1959). 60 cents.

Highway Cost Allocation Study:
Final Report, Parts I–V, House Document No. 54 (1961). 70 cents.
Supplementary Report, House Document No. 124 (1965). $1.00.

Maximum Desirable Dimensions and Weights of Vehicles Operated on the Federal-Aid Systems, House Document No. 354 (1964). 45 cents.

The 1965 Interstate System Cost Estimate, House Document No. 42 (1965). 20 cents.

PUBLICATIONS

A Quarter Century of Financing Municipal Highways, 1937–61, $1.00.

Accidents on Main Rural Highways—Related to Speed, Driver, and Vehicle (1964). 35 cents.

Aggregate Gradation for Highways: Simplification, Standardization, and Uniform Application, and A New Graphical Evaluation Chart (1962). 25 cents.

America's Lifelines—Federal Aid for Highways (1962). 15 cents.

Capacity Charts for the Hydraulic Design of Highway Culverts (Hydraulic Engineering Circular, No. 10) (1965). 65 cents.

Classification of Motor Vehicles, 1956–57 (1960). 75 cents.

Design Charts for Open-Channel Flow (1961). 70 cents.

Design of Roadside Drainage Channels (1965). 40 cents.

Federal Laws, Regulations, and Other Material Relating to Highways (1960). $1.00.

Highway Bond Financing . . . An Analysis, 1950–1962. 35 cents.

Highway Finance 1921–1962 (a statistical review by the Office of Planning, Highway Statistics Division) (1964). 15 cents.

Highway Planning Map Manual (1963). $1.00.

Highway Planning Technical Reports—Creating, Organizing, and Reporting Highway Needs Studies (1964). 15 cents.

Highway Research and Development Studies, Using Federal-Aid Research and Planning Funds (1964). $1.00.

PUBLICATIONS—Continued

Highway Research and Development Studies, Using Federal-Aid Research and Planning Funds (May 1965). 75 cents.

Highway Statistics (published annually since 1945):
1956, $1.00. 1957, $1.25. 1958, $1.00. 1959, $1.00. 1960, $1.25. 1962, $1.00. 1963, $1.00.

Highway Statistics, Summary to 1955. $1.00.

Highway Transportation Criteria in Zoning Law *and* Police Power and Planning Controls for Arterial Streets (1960). 35 cents.

Highways and Economic and Social Changes (1964). $1.25.

Hydraulics of Bridge Waterways (1960). 40 cents.

Increasing the Traffic-Carrying Capability of Urban Arterial Streets: The Wisconsin Avenue Study (1962). Out of print. Appendix, 70 cents.

Interstate System Route Log and Finder List (1963). 10 cents.

Labor Compliance Manual for Direct Federal and Federal-Aid Construction, 2d ed. (1965). $1.75.

Landslide Investigations (1961). 30 cents.

Manual for Highway Severance Damage Studies (1961). $1.00.

Manual on Uniform Traffic Control Devices for Streets and Highways (1961). $2.00.
Part V—Traffic Controls for Highway Construction and Maintenance Operations (1963). 25 cents.

Opportunities for Young Engineers in the Bureau of Public Roads (1965). 30 cents.

Reinforced Concrete Pipe Culverts—Criteria for Structural Design and Installation (1963). 30 cents.

Road-User and Property Taxes on Selected Motor Vehicles, 1964. 45 cents.

Selected Bibliography on Highway Finance (1951). 60 cents.

Specifications for Aerial Surveys and Mapping by Photogrammetric Methods for Highways (1958): a reference guide outline. 75 cents.

Standard Plans for Highway Bridges (1962):
Vol. I—Concrete Superstructures. $1.00.
Vol. II—Structural Steel Superstructures. $1.00.
Vol. III—Timber Bridges. $1.00.
Vol. IV—Typical Continuous Bridges. $1.00.
Vol. V—Typical Pedestrian Bridges. $1.00.

The Identification of Rock Types (revised edition, 1960). 20 cents.

The Role of Economic Studies in Urban Transportation Planning (1965). 45 cents.

Traffic Assignment and Distribution for Small Urban Areas (1965). $1.00.

Traffic Assignment Manual (1964). $1.50.

Traffic Safety Services, Directory of National Organizations (1963). 15 cents.

Transition Curves for Highways (1940). $1.75.