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A METHOD OF COMPUTING LIVE LOADS TRANSMITTED TO UNDERGROUND CONDUITS

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SYNOPSIS

More than twenty years ago the Iowa Engineering Experiment Station conducted experiments which indicated rather definitely that the load transmitted to an underground conduit by a truck wheel applied at a roadway surface may be safely computed by the Boussinesq formula for a point load applied at the surface of a semi-infinite elastic solid. Up until about 1929, the usual procedure for computing live loads on such structures was to subdivide the top of the conduit into a number of small sub-areas and calculate the load on each sub-area by means of this formula. The summation of loads on all the sub-areas gave the total load on the section of conduit caused by a wheel load at the roadway surface. In 1929, Dr. D. L. Holl integrated the Boussinesq formula to obtain the pressure over a finite rectangular area in the undersoil. The result of this integration was a rather lengthy expression whose evaluation was not difficult, but was rather tedious.

In 1935 Dr. N. M. Newmark integrated the Boussinesq formula for the purpose of evaluating the pressure at a point in the undersoil due to a uniformly distributed load applied over a rectangular area at the soil surface. This problem was directed toward the determination of pressure at various points in the undersoil for the purpose of estimating the probable settlement of buildings and other structures resting on soil foundations. In connection with this solution, Newmark presented a table of ratios which greatly simplified the solution of his formula.

Although Holl's problem and that of Newmark were directed toward different

objectives, they both involved the integration of the Boussinesq formula over a rectangular area and the similarity between the two solutions is apparent. The authors have demonstrated that the Newmark table can be used to solve Holl's equation, and suggest that its use will greatly simplify the application of that equation to the determination of live loads on underground conduits. A reproduction of Newmark's table is included in the paper for convenience, and several examples of its application in the solution of Holl's equation are given.

The total vertical load on an underground conduit, such as a culvert or drain is equal to the load produced by the earth overburden plus the load transmitted through the overburden from live loads applied at the ground surface. These live loads, such as truck wheels, airplane wheels or similar traffic units, may produce loads on an underground conduit which are greatly in excess of the load due to the earth in cases where the depth of cover is relatively shallow, and the computation of the amount of load transmitted to the structure becomes extremely important in the structural design of the conduit. The purpose of this paper is to present a simplified method of computing these transmitted live loads.

Very extensive experimental studies which were conducted more than twenty years ago at the Iowa Engineering Experiment Station[1] indicated rather definitely that the load transmitted to an underground conduit by a truck wheel applied at the roadway surface may be safely computed by means of the Boussinesq formula for a point load applied at the surface of a semi-infinite elastic solid. This Boussinesq formula for vertical pressure is

$$\sigma_z = \frac{3P}{2\pi}\frac{z^3}{R^5} \qquad (1)$$

in which:

- σ_z = the vertical unit pressure at a point whose coordinates are x, y and z,
- P = a concentrated load applied at the surface and at the origin of coordinates,
- z = the depth to the point xyz,
- R = the slant height from the load to the point xyz. $R = \sqrt{x^2 + y^2 + z^2}$.

These experiments also revealed that the live load on a culvert is essentially the same regardless of whether the culvert is circular or rectangular in shape and that the proper depth of cover to use when computing the live load on a circular conduit is the distance from the top of the conduit to the ground surface. In other words, the live load on a circular conduit is the same as that computed on the projection of the conduit on a horizontal plane passing through its top element. In addition, quantitative values of an impact factor by which the static live load should be increased when the traffic loads are moving loads were obtained from these experimental studies.

As a result of these experiments, Dean Marston,[2] under whose direction this work was conducted, proposed the following formula for loads on underground conduits due to concentrated super-imposed traffic loads.

$$W_t = \frac{1}{A} I_c C_t T \qquad (2)$$

in which:

- W_t = average load per unit length of conduit,
- A = length of conduit section on which load is computed,
- I_c = impact factor for moving load,
- C_t = load coefficient,
- T = a concentrated surface load.

Until about 1929 the usual procedure for determining values of C_t for use in eq. (2) was to divide the top of the conduit section (or the horizontal projection of a circular pipe section) into a number of small sub-areas and compute a coefficient for each sub-area by the Boussinesq formula (1). The summation of these sub-coefficients provided the coefficient for computing the load on the total area of the conduit section.

In 1929, Dr. D. L. Holl,[3] completed the

[1] Spangler, M. G., Clyde Mason and Robley Winfrey. "Experimental Determinations of Static and Impact Loads Transmitted to Culverts." Bul. 79, Iowa Engineering Experiment Station, 1926.

[2] Marston, Anson, "The Theory of External Loads on Closed Conduits in the Light of the Latest Experiments." Bul. 96, Iowa Engineering Experiment Station, 1930 (out of print).

[3] Professor and Head, Mathematics Dept., Iowa State College.

integration of the vertical load imposed by a concentrated surface load on a horizontal plane of finite dimensions in the undersoil in accordance with the Boussinesq solution. The result of this integration was published by Marston[4] in the form

$$C_t = 1 - \frac{2}{\pi} \cdot \left[\left(\sin^{-1} H \sqrt{\frac{\frac{A^2}{4} + \frac{B_c^2}{4} + H^2}{\left(\frac{A^2}{4} + H^2\right)\left(\frac{B_c^2}{4} + H^2\right)}}\right) - \frac{\frac{AB_cH}{4}}{\sqrt{\frac{A^2}{4} + \frac{B_c^2}{4} + H^2}}\left(\frac{1}{\frac{A^2}{4} + H} + \frac{1}{\frac{B_c^2}{4} + H}\right)\right] \quad (3)$$

in which:

B_c = the outside width of the conduit,
A = the length of the conduit section,
H = the vertical height from the top of the conduit to the ground surface.

A diagrammatic representation of Holl's problem is shown in Figure 1.

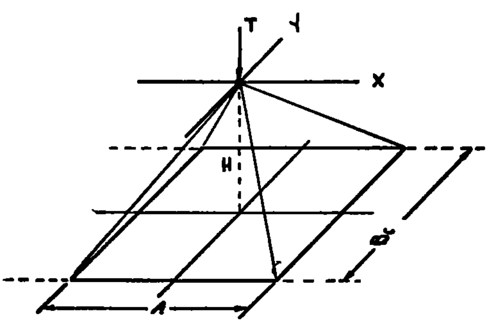

Figure 1. Holl's Problem

In 1935, Dr. Nathan M. Newmark[5] published a method of computing the vertical unit pressure in an elastic foundation material due to a uniformly distributed load applied over a finite area at the surface of the material (the soil). This problem was directed toward the determination of the pressure at various points in the undersoil for the purpose of estimating the probable settlement of buildings and other structures resting on soil foundations. It involved the integration of Boussinesq's formula for the case of a load distributed over a rectangular area. The resulting formula for the unit pressure at a point in the undersoil at a depth Z directly under one corner of a loaded rectangle of dimensions X and Y is[6]

$$\sigma_z = \frac{W}{4\pi}\left[\frac{2XYZ\sqrt{X^2 + Y^2 + Z^2}}{Z^2(X^2 + Y^2 + Z^2) + X^2 Y^2} \cdot \frac{X^2 + Y^2 + 2Z^2}{X^2 + Y^2 + Z^2} + \left(\sin^{-1} \frac{2XYZ\sqrt{X^2 + Y^2 + Z^2}}{Z^2(X^2 + Y^2 + Z^2) + X^2 Y^2}\right)\right] \quad (4)$$

A diagram illustrating Newmark's problem is shown in Figure 2.

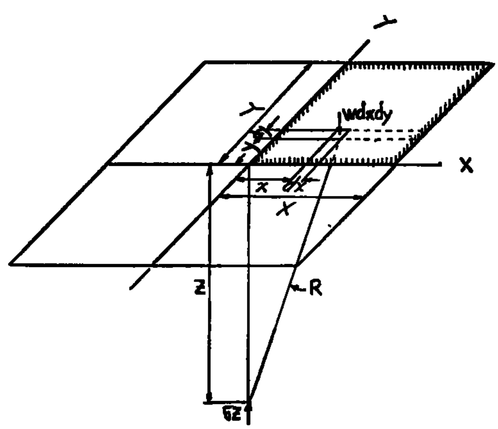

Figure 2. Newmark's Problem—Uniformly Distributed Load

An important feature of Newmark's presentation of the solution of this problem was the inclusion of a table of values of $\frac{\sigma}{w}$ by which

[4] op. cit.

[5] Newmark, Nathan M., "Simplified Computation of Vertical Pressures in Elastic Foundations," Circular No. 24, Engineering Experiment Station, University of Illinois, 1935.

[6] As an alternate form, the term in parenthesis may be written

$$\tan^{-1} \frac{2XYZ\sqrt{X^2 + Y^2 + Z^2}}{Z^2(X^2 + Y^2 + Z^2) - X^2Y^2}$$

the solution of equation 4 was greatly simplified. In the preparation of this table, of the loaded area to the depth to the point in question and select the tabular value corre-

TABLE 1
VERTICAL PRESSURE AT UNIT DEPTH UNDER CORNER OF RECTANGLE OF DIMENSIONS m BY n, LOADED UNIFORMLY; VALUES ARE FOR $\frac{\sigma}{w}$

m	n = 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4
0.1	0.00470	0.00917	0.01323	0.01678	0.01978	0.02223	0.02420	0.02576	0.02698	0.02794	0.02926	0.03007
0.2	0.00917	0.01790	0.02585	0.03280	0.03866	0.04348	0.04735	0.05042	0.05283	0.05471	0.05733	0.05894
0.3	0.01323	0.02585	0.03735	0.04742	0.05593	0.06294	0.06858	0.07308	0.07661	0.07938	0.08323	0.08561
0.4	0.01678	0.03280	0.04742	0.06024	0.07111	0.08009	0.08734	0.09314	0.09770	0.10129	0.10631	0.10941
0.5	0.01978	0.03866	0.05593	0.07111	0.08403	0.09473	0.10340	0.11035	0.11584	0.12018	0.12626	0.13003
0.6	0.02223	0.04348	0.06294	0.08009	0.09473	0.10688	0.11679	0.12474	0.13105	0.13605	0.14309	0.14749
0.7	0.02420	0.04735	0.06858	0.08734	0.10340	0.11679	0.12772	0.13653	0.14356	0.14914	0.15703	0.16199
0.8	0.02576	0.05042	0.07308	0.09314	0.11035	0.12474	0.13653	0.14607	0.15371	0.15978	0.16843	0.17389
0.9	0.02698	0.05283	0.07661	0.09770	0.11584	0.18105	0.14356	0.15371	0.16185	0.16835	0.17766	0.18357
1.0	0.02794	0.05471	0.07938	0.10129	0.12018	0.13605	0.14914	0.15978	0.16835	0.17522	0.18508	0.19139
1.2	0.02926	0.05733	0.08323	0.10631	0.12626	0.14309	0.15703	0.16843	0.17766	0.18508	0.19584	0.20278
1.4	0.03007	0.05894	0.08561	0.10941	0.13003	0.14749	0.16199	0.17389	0.18357	0.19139	0.20278	0.21020
1.6	0.03058	0.05994	0.08709	0.11135	0.13241	0.15028	0.16515	0.17739	0.18737	0.19546	0.20731	0.21510
1.8	0.03090	0.06058	0.08804	0.11260	0.13395	0.15207	0.16720	0.17967	0.18986	0.19814	0.21032	0.21836
2.0	0.03111	0.06100	0.08867	0.11342	0.13496	0.15326	0.16856	0.18119	0.19152	0.19994	0.21235	0.22058
2.5	0.03138	0.06155	0.08948	0.11450	0.13628	0.15483	0.17036	0.18321	0.19375	0.20236	0.21512	0.22364
3.0	0.03150	0.06178	0.08982	0.11495	0.13684	0.15550	0.17113	0.18407	0.19470	0.20341	0.21633	0.22494
4.0	0.03158	0.06194	0.09007	0.11527	0.13724	0.15598	0.17168	0.18469	0.19540	0.20417	0.21722	0.22600
5.0	0.03160	0.06199	0.09014	0.11537	0.13737	0.15612	0.17185	0.18488	0.19561	0.20440	0.21749	0.22632
6.0	0.03161	0.06201	0.09017	0.11541	0.13741	0.15617	0.17191	0.18496	0.19569	0.20449	0.21760	0.22644
8.0	0.03162	0.06202	0.09018	0.11543	0.13744	0.15621	0.17195	0.18500	0.19574	0.20455	0.21767	0.22652
10.0	0.03162	0.06202	0.09019	0.11544	0.13745	0.15622	0.17196	0.18502	0.19576	0.20457	0.21769	0.22654
∞	0.03162	0.06202	0.09019	0.11544	0.13745	0.15623	0.17197	0.18502	0.19577	0.20458	0.21770	0.22656

m	n = 1.4	1.6	1.8	2.0	2.5	3.0	4.0	5.0	6.0	8.0	10.0	∞
0.1	0.03007	0.03058	0.03090	0.03111	0.03138	0.03150	0.03158	0.03160	0.03161	0.03162	0.03162	0.03162
0.2	0.05894	0.05994	0.06058	0.06100	0.06155	0.06178	0.06194	0.06199	0.06201	0.06202	0.06202	0.06202
0.3	0.08561	0.08709	0.08804	0.08867	0.08948	0.08982	0.09007	0.09014	0.09017	0.09018	0.09019	0.09010
0.4	0.10941	0.11135	0.11260	0.11342	0.11450	0.11495	0.11527	0.11537	0.11541	0.11543	0.11544	0.11544
0.5	0.13003	0.13241	0.13395	0.13496	0.13628	0.13684	0.13724	0.13737	0.13741	0.13744	0.13745	0.13745
0.6	0.14749	0.15028	0.15207	0.15326	0.15483	0.15550	0.15598	0.15612	0.15617	0.15621	0.15622	0.15623
0.7	0.16199	0.16515	0.16720	0.16856	0.17036	0.17113	0.17168	0.17185	0.17191	0.17195	0.17196	0.17197
0.8	0.17389	0.17739	0.17967	0.18119	0.18321	0.18407	0.18469	0.18488	0.18496	0.18500	0.18502	0.18502
0.9	0.18357	0.18737	0.18986	0.19152	0.19375	0.19470	0.19540	0.19561	0.19569	0.19574	0.19576	0.19577
1.0	0.19139	0.19546	0.19814	0.19994	0.20236	0.20341	0.20417	0.20440	0.20449	0.20455	0.20457	0.20458
1.2	0.20278	0.20731	0.21032	0.21235	0.21512	0.21633	0.21722	0.21749	0.21760	0.21767	0.21769	0.21770
1.4	0.21020	0.21510	0.21836	0.22058	0.22364	0.22499	0.22600	0.22632	0.22644	0.22652	0.22654	0.22656
1.6	0.21510	0.22025	0.22372	0.22610	0.22940	0.23088	0.23200	0.23236	0.23249	0.23258	0.23261	0.23263
1.8	0.21836	0.22372	0.22736	0.22986	0.23334	0.23495	0.23617	0.23656	0.23671	0.23681	0.23684	0.23686
2.0	0.22058	0.22610	0.22986	0.23247	0.23614	0.23782	0.23912	0.23954	0.23970	0.23981	0.23985	0.23987
2.5	0.22364	0.22940	0.23334	0.23614	0.24010	0.24196	0.24344	0.24392	0.24412	0.24425	0.24429	0.24432
3.0	0.22499	0.23088	0.23495	0.23782	0.24196	0.24394	0.24554	0.24608	0.24630	0.24646	0.24650	0.24654
4.0	0.22600	0.23200	0.23617	0.23912	0.24344	0.24554	0.24729	0.24791	0.24817	0.24836	0.24842	0.24846
5.0	0.22632	0.23236	0.23656	0.23954	0.24392	0.24608	0.24791	0.24857	0.24885	0.24907	0.24914	0.24919
6.0	0.22644	0.23249	0.23671	0.23970	0.24412	0.24630	0.24817	0.24885	0.24916	0.24939	0.24946	0.24952
8.0	0.22652	0.23258	0.23681	0.23981	0.24425	0.24646	0.24836	0.24907	0.24939	0.24964	0.24973	0.24980
10.0	0.22654	0.23261	0.23684	0.23985	0.24429	0.24650	0.24842	0.24914	0.24946	0.24973	0.24981	0.24989
∞	0.22656	0.23263	0.23686	0.23987	0.24432	0.24654	0.24846	0.24919	0.24952	0.24980	0.24989	0.25000

$$m = \frac{X}{Z} \quad \text{and} \quad n = \frac{Y}{Z}$$

To use the table it is only necessary to calculate the ratios of the length and the width sponding to these ratios. This tabular value may then be multiplied by the unit load w, to obtain the unit pressure at a point at depth Z under a corner of the loaded area. Newmark's table which appears on pages 10 and

11 of reference [6] is reproduced here (with Dr. Newmark's permission) for convenience as Table 1.

Although Holl's problem and that of Newmark were directed toward different objectives, they both involved the integration of the Boussinesq formula over a rectangular area and the similarity between the two solutions is apparent. The author's have demonstrated that the Newmark table can be used to solve Holl's equation 3, and suggest that its use will greatly simplify the application of that equation to the determination of live loads on under ground conduits. If

$$m = \frac{A}{2H} \text{ and } n = \frac{B_c}{2H} \text{ (or vice versa)}$$

the tabular value corresponding to m and n is the value of C_t for a rectangle of dimensions $\frac{A}{2}$ and $\frac{B_c}{2}$ when a concentrated load such as a

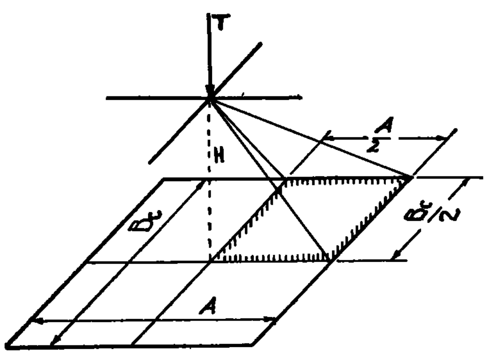

Figure 3

truck wheel is placed directly over one corner of the rectangle and at the distance H above it, as illustrated in Figure 3. To obtain C_t for the complete rectangle, A by B_c, when the load is situated directly above the center of the area, it is only necessary to multiply the tabular value by 4.

Example 1. Assume a culvert pipe section 6 ft. long and 4 ft. outside diameter under 4 ft. of cover. Compute the total load on the section due to a 10,000-lb. wheel load directly above the center of the pipe.

$$m = \frac{6}{2 \times 4} = 0.75 \qquad n = \frac{4}{2 \times 4} = 0.5$$

The value in Table 1 corresponding to these values of m and n (interpolating between m = 0.7 and 0.8) is 0.10687. Multiplying by 4 gives 0.42748 which is the value of C_t for the live load on this culvert section. To obtain lhe total static live load caused by the wheel toad, multiply 10,000 by 0.42748 = 4,275 lb. If an impact factor is appropriate to the situation, it should be multiplied by this static live load to obtain live load plus impact.

Newmark's table may also be used in determining the vertical load on an underground conduit section due to a concentrated surface load which is laterally displaced from the vertical axis through the center of the section by considering a series of rectangles whose corners are directly beneath the applied load.

Example 2. Assume the culvert section of Example 1 is acted upon by a 10,000-lb. wheel load on the longitudinal axis of the pipe (extended) and at a distance of 6 ft. from the vertical axis through the center of the section. The layout of load and pipe section on which it is desired to compute the transmitted live load is shown in Figure 4.

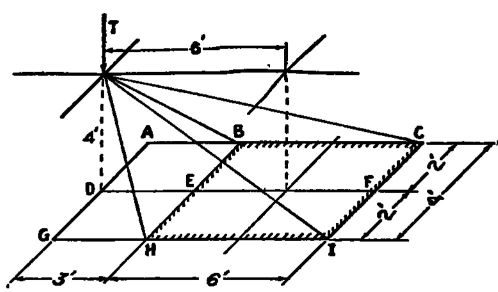

Figure 4. Rectangle *BCHI* = *ACGI* — *ABGH*

First consider the two symmetrically placed rectangles *ACDF* and *DFGI*. For each of these rectangles

$$m = \tfrac{9}{4} = 2.25 \text{ and } n = \tfrac{2}{4} = 0.5$$

The tabular value (Table 1) corresponding to these values of m and n is 0.13562 and since there are two rectangles, 2 × 0.13562 = 0.27124 is the coefficient which applies to the area *ACGI*.

Next it will be necessary to subtract the coefficient which applies to the rectangle *ABGH*. To obtain this coefficient, consider the two rectangles *ABDE* and *DEGH*, for which

$$m = \tfrac{3}{4} = 0.75 \text{ and } n = \tfrac{2}{4} = 0.5$$

The corresponding coefficient is 0.10687. Multiplying by 2 gives 0.21374.

Subtracting 0.21374 from 0.27124 gives 0.05750, which is the net coefficient for the area *BCHI*. Multiplying 0.05750 by 10,000 = 575 lb. as the static live load on the culvert section.

By combining the results of examples 1 and 2, the live load on the conduit section *BCHI* due to two wheel loads of 10,000 lb. each, one of which is placed at the roadway surface above the center of the culvert section and the other 6 ft. away above the longitudinal center line of the section may be computed. This is representative of the load situation produced by two rear wheels of a truck on the roadway. This procedure may be extended to embrace the problem of determining live loads due to four wheel loads in a line such as might be the case for two passing trucks on a roadway.

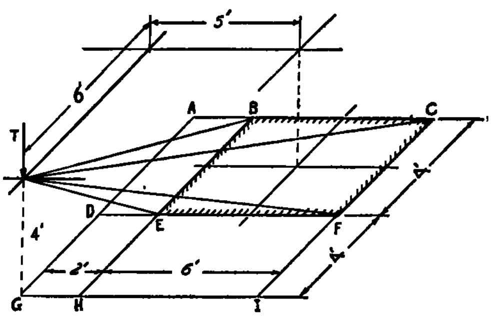

Figure 5. Rectangle *BCFE* = *ACIG* — *ABHG* — *DFIG* + *DEHG*

Example 3. Assume the culvert section of Example 1 is acted upon by a 10,000-lb. wheel load which is not on either the longitudinal or the transverse axis of the section, as indicated by the layout in Figure 5. In this case the wheel is placed 5 ft. to the left and 6 ft. on the near side of the vertical axis through the center of the section.

First determine the coefficient for the large rectangle *ACGI*, for which

$$m = \tfrac{8}{4} = 2 \qquad \text{and } n = \tfrac{8}{4} = 2$$

The tabular value (Table 1) is 0.23247.

Consider next the rectangle *ABGH*, for which

$m = \tfrac{2}{4} = 0.5$ and $n = \tfrac{8}{4} = 2.$

The tabular value is 0.13496.

For rectangle *DFGI*

$m = \tfrac{8}{4} = 2$ and $n = \tfrac{4}{4} = 1.$

The tabular value is 0.19994

For rectangle *DEGH*

$m = \tfrac{2}{4} = 0.5$ and $n - \tfrac{4}{4} = 1.$

The tabular value is 0.12018.

Rectangle *BDEF* = *ACGI* − *ABGH* − *DFGI* + *DEGH*

Therefore C_t for the culvert section *BCEF* is

$$C_t = 0.23247 - 0.13496 - 0.19994 + 0.12018 = 0.01775$$

0.01775 × 10000 = 178 lb. which is the live load on culvert section *ABDE* from a 10,000-lb. wheel load placed as shown in Figure 5 and applied at the roadway surface 4 ft. above the top of the culvert.

In the examples the applied wheel loads were considered to be concentrated at a point when calculating the live loads transmitted to underground conduits. Both experimental research and theoretical considerations indicate the validity of this assumption for the case of truck wheel loads and depths of cover which are practical in culvert construction. In the case of conduits under airfield runways, the surface loads of greatest magnitude will be applied through airplane wheels having relatively large contact areas between tires and runway surfaces. It is believed that the procedures indicated herein are valid for this latter situation, but it may be necessary to subdivide the applied loaded area into smaller areas in accordance with the criterion that the longest dimension of the applied load subareas should not exceed one-half the depth to the conduit in order to treat the applied load as a concentrated load without appreciable error.

DISCUSSION

MR. E. S. BARBER, *Public Roads Administration:* For rapid interpolation Table 1 may be plotted as in Figure A.

Figure B shows the average loads transmitted to rectangular areas in an elastic medium from loads uniformly distributed over circular areas at the surface with radii from 6 to 18 in. It is evident that the size of loaded area has appreciable effect for shallow thicknesses of cover. At depths greater than six times the radius, a point load may be assumed and the values were in fact calculated from Newmark's table. Since the pressure on the pipe is not uniform, some effective length must be used for design; Figure B considers 2-ft and 3-ft lengths.

For comparison with example 1, Figure B gives 88 lb per lin ft averaged over a 3-ft length for a 1000-lb load distributed over an area with a radius of 6 in., 4 ft above the pipe with a diameter of 4 ft. For the 10,000-lb load this gives 880 lb per lin ft, compared to $\frac{4275}{6} = 712$ lb per lin ft averaged over a 6-ft length. For a 3-ft length, Table 1 or Figure A gives $C_t = 0.067 \times 4 = 0.268$ or $\frac{0.268 \times 10{,}000}{3} = 893$ lb per lin ft for a load applied at a point which is slightly higher than the 880 lb for a distributed load.

Figures C through G are extensions of Figure B to include loads not directly over the area on which the transmitted load is calculated.

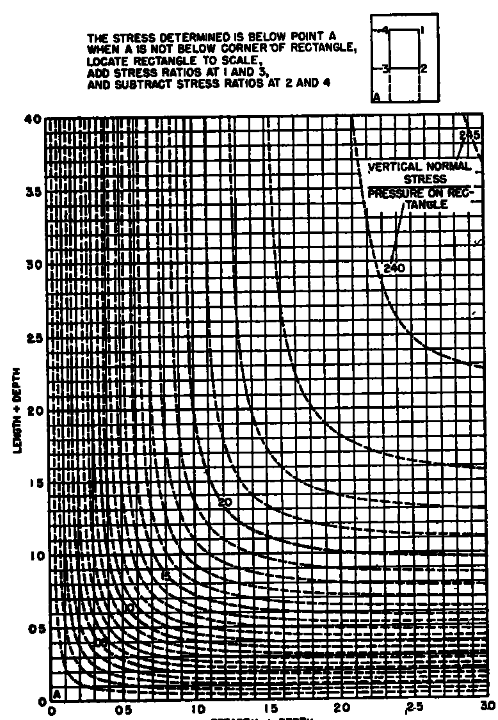

Figure A. Graph of Vertical Normal Stress Under Corner of Rectangle Loaded with Unit Pressure.

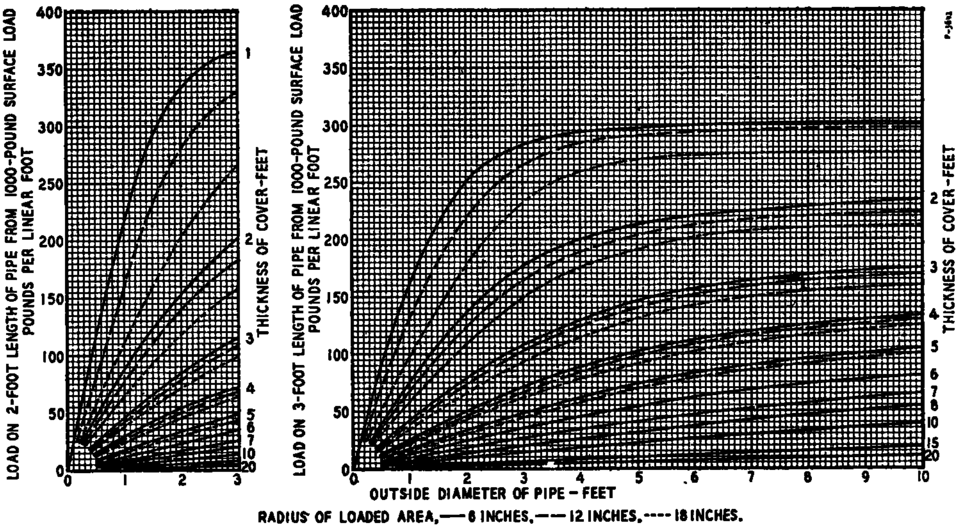

Figure B. Vertical Loads Transmitted to Buried Pipes from Loads at the Surface Directly Over the Pipe

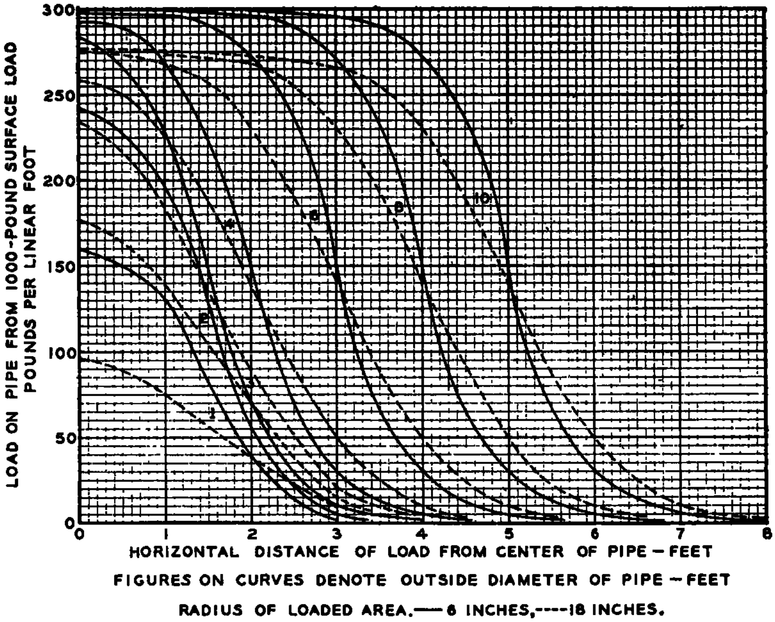

Figure C. Vertical Loads Transmitted to Buried Pipes (3-ft Length) from Loads at Surface. Thickness of Cover, 1 ft

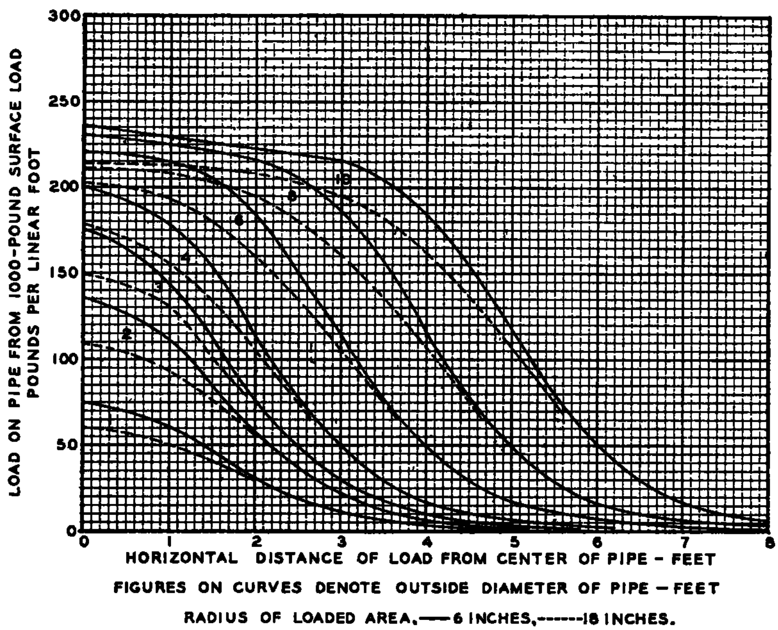

Figure D. Vertical Loads Transmitted to Buried Pipe (3-ft Length) from Load at Surface. Thickness of Cover, 2 ft

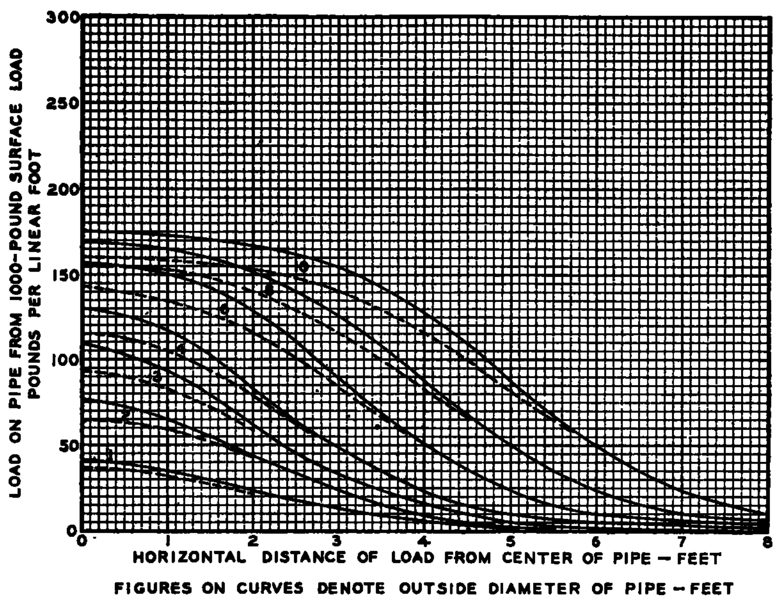

Figure E. Vertical Loads Transmitted to Buried Pipe (3-ft Length) from Loads at Surface. Thickness of Cover, 3 ft

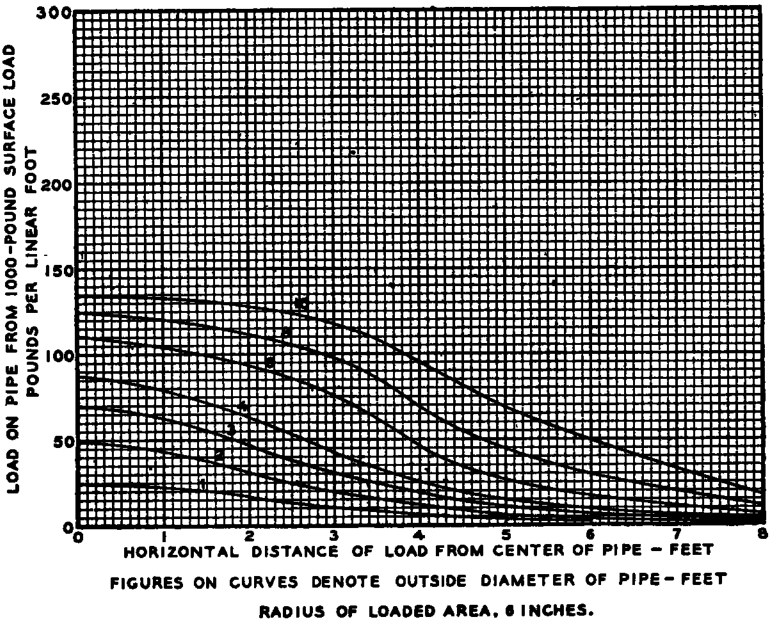

Figure F. Vertical Loads Transmitted to Buried Pipe (3-ft Length) from Loads at Surface. Thickness of Cover, 4 ft

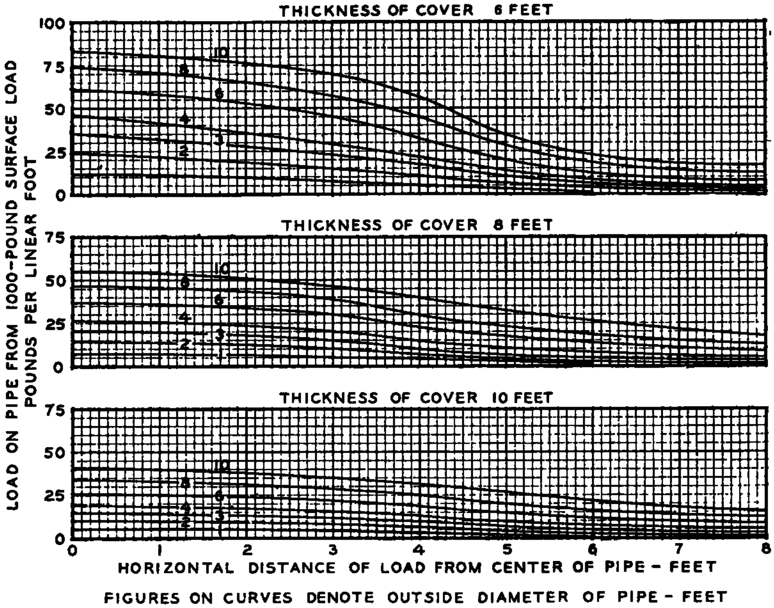

Figure G. Vertical Loads Transmitted to Buried Pipe (3-ft Length) from Loads at Surface. Radius of Loaded Area, 6 in