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SYNOPSIS The stability of large metal culverts depends on the performance of the backfill around the pipe, which must be considered as a part of the structure when evaluating its safety. A simplified method to evaluate the current stability of such a structure on the basis of the structure's shape is derived. Useful when limited amount of information is available, this method provides an economical procedure for: (1) evaluating the condition of the existing backfill and its capability to provide a safe support for the structure; (2) predicting final movements and determining if additional investigations are necessary to establish the safety of the structure; and (3) determining if measured deflections are in agreement with those predicted and, if not, determining if the safety of the structure is endangered by phenomena other than the expected behavior of surrounding soil (e.g. voids near pipe, soil erosion, non-symmetric loadings).

INTRODUCTION

Several hundred long-span corrugated metal pipes are currently in place across the United States and about one-hundred new pipes are installed each year. Since most of the pipes are installed under highways and the safety of traffic relies on their structural stability, periodic inspection and evaluation is obligatory. Because the stability of these structures depends on the condition of the supporting backfill, and because extensive annual evaluation of the backfill is expensive and impractical in most cases, a simplified method, based on a limited amount of available information, is necessary.

Corrugated metal pipes cannot be rated based on structural capabilities, as can a bridge. These pipes depend on the backfill for their support, and the backfill around the pipe must be considered as a part of the structure. Any evaluation of large corrugated metal pipes must, therefore, take into consideration performance of the backfill. The overall performance of the pipe and backfill can be evaluated by comparing the shape of the pipe with the intended design shape, both at time of installation and periodically thereafter.

The procedure presented describes a relatively simple procedure for evaluating the condition of a long-span pipe based on shape and then, if the shape is approaching a degree of flatness which may be unstable, for utilizing the density of the backfill and the soil type to predict future movement. The method can be used to determine future movements of pipes which are experiencing deflection or to project deflection of a newly installed pipe.

EVALUATION OF PIPE CONDITION BASED ON SHAPE

The important factor to be evaluated in assessing the safety of a corrugated metal structure is the extent to which the pipe wall has lost its curvature and becomes flatter. The extent of flattening can be measured during an annual inspection using the method recommended by Cowherd and Delger (1986). This procedure evaluates the changes in shape to determine whether or not the amount of deflection creates a problem. For this purpose, a computer program entitled "MULTSPAN" was prepared. This program:

- calculates the radii along the structure perimeter based on the chord and mid-ordinate measurements (see Figure 1), determines the average, maximum and minimum values for the chords, mid-ordinates, and radii;
- compares these field values with design values, corresponding to the structure's intended shape;
- where there is no design information available, the program estimates what these dimensions should be using the available field data and calculates estimated mid-ordinates based on the properties of circular areas; and

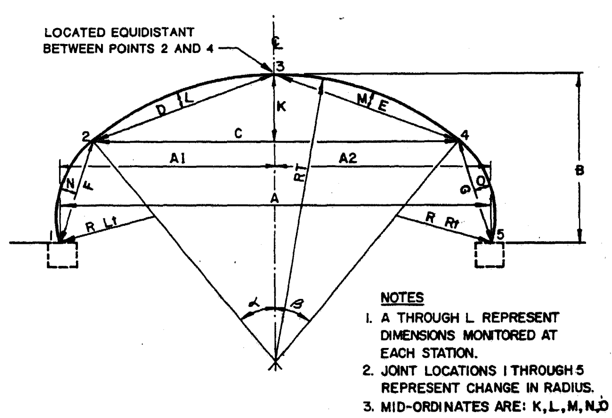

Fig. 1 Measured and Computed Parameters

uses the deflection data and visual observations to assess the degree of flatness and make recommendations of appropriate action.

Details on MULTSPAN can be found in Thrasher and Perlea (1986). The MULTSPAN analysis, along with pipe condition data, can be used to establish a bridge rating. This bridge rating system is compatible with the Bridge Inventory and Inspection Program. The method assesses the deflection (measured in an annual Bridge Inspection Program) to make recommendations relative to remedial action. Table I shows the recommended actions provided by MULTSPAN relative to the various amount of mid-ordinate deflections (Cowherd and Degler, 1986).

TABLE I. Percent Mid-Ordinate Change and Remedial Action

Mid-Ordinate Percent Change	Depth of Cover (ft)	Recommended Action
<15	Any	No action required.
15 - 20	Over 6.0	No action required.
	Under 6.0	Monitor on 6-month interval.
20 - 25	Over 6.0	Reduce legal load to 90% of H-20 and monitor on 6-month intervals.
	Under 6.0	Reduce legal load to 75% of H-20 and monitor on 6-month intervals.
25 - 30	Over 6.0	Reduce legal load to 75% of H-20 and monitor on 6-month intervals.
	3.0 - 6.0	Reduce legal load to 50% of H-2 and monitor on 6-month intervals.
	Under 3.0	Reduce legal load to 50% and do detailed analysis.
>30	Any	Close road until detailed analysis is done.

NOTE: Detailed analysis to include soil borings to determine expected additional movement.

Figure 1 illustrates the measured parameters. The Table I recommendations are based on mid-ordinate deflections and not on total span heights. Such recommendations for corrective action have been based on the extensive experience of the manufacturers and a hand full of practicioners. A more rigorous analysis of these structures can be made, however, based on the assumption that they behave in a manner similar to thin wall tubes subjected to uniform loading.

Defining the factor of safety (F) as the ratio between the critical soil pressure which induces buckling failure and the actual soil pressure, and using relationships between mid-ordinate (m) and other geometrical parameters of the pipe, the following equation may be written (Cowherd et al., 1986):

$$\Delta F/F = (\Delta m/m) \times 3\ (1 - m/r) \qquad (1)$$

Where r is the radius corresponding to the mid-ordinate m.

For standard long-span pipes the factor 3 (1 - m/r) varies generally between 2.3 and 2.8. That means that a pipe having initially a factor of safety of about 5 will have the factor of safety decreased to 2.9-3.3 when the mid-ordinate percent change is 15%, around 2.5 for 20%, around 1.8 for 25%, and close to 1.0 for 30%.

For various types of pipes and other initial factors of safety the results of such an analysis would differ, but not significantly, so that the criteria in Table I appear reasonable.

ESTIMATING STRUCTURE MOVEMENT

If the structure movement is enough to warrant borings to determine the nature of the backfill, the borings are made and appropriate soil data collected. The soil data are then introduced into the computer program to make projections of both magnitude and rate of continued movement. To determine the soil density and soil type, it is necessary to make at least one boring on either side of the pipe in the backfill and preferably at least one boring in the material outside the backfill. The method can use either density measurements directly or standard penetration values which can be correlated to density. The density can be determined with nuclear depth-density gauges throughout the depth of a boring or by taking undisturbed samples. The nuclear density method is by far the most economical.

The accuracy of this method has been evaluated using several different case histories; some of which are presented in this paper. In all cases, good agreement between the predicted and actual movement was observed. The main advantage of the method is that it presents a simple way of assessing the safety of a corrugated metal structure without requiring considerable expensive field and laboratory data and computer time to predict continued movement of a pipe that is experiencing deflection. It can also be used to predict total movement using initial compaction data. As a result, a relatively simple assessment of projected pipe movement can be made. Vertical movement of the structure, when due to the deformation of the pipe and not to a general settlement, is of greatest importance since it is a measure of the degree of flatness of the structures crown.

Except for unusual loading conditions previously noted, the vertical movement of a quasi-circular structure can be related to horizontal or side movement of the structure by a factor of approximately one-half; i.e., the movement of one side of the structure into the backfill is equal to approximately one-half the vertical movement (Spangler, 1951). Actually, the shape factor; i.e., the ratio between the movement of one side of the structure and the corresponding vertical movement, varies for usual shapes between 1.4 and 4.9. The program MULTSPAN makes an evaluation of the shape factor based on the assumption that during small deformations of pipe the mid-ordinates only change, but the chord lengths remain unchanged, which leads to the following relationship (see Fig. 4 for notations):

$$\frac{\Delta R}{\Delta(S/2)} = \frac{1}{2}[(S - S_B) / R_B + S/(R - R_B)] \qquad (2)$$

Therefore, determination of the outward horizontal movement will also permit determination of downward movement. The calculation of this horizontal movement may be accomplished by a simplified, three step process:

- Step No. 1 - determine the soil compressibility,
- Step No. 2 - determine the maximum horizontal pressure exerted by the structure on the surrounding fill; and
- Step No. 3 - calculate the horizontal movement using classical theory of consolidation for shallow foundation settlement.

Step No. 1 - Determination of Soil Compressibility

An estimation of the final movement of a structure can be based on the result of a consolidation test with zero lateral movement. This method has been used for many years to evaluate settlement of building foundations. The method can be applied to horizontal (and thus vertical) movement of pipes by considering the side of the pipe as a shallow footing.

This method does not take into account such factors as:

- the variation of the compressibility indexes with the stress level,
- the instantaneous (elastic) compression,
- the secondary compression; and
- the influence of the actual distribution of stresses on the structure.

Experience (with both buildings and long-span corrugated metal pipes) has shown, however, that this method provides an adequate measure of movement for both buildings and pipes. It is the standard method for predicting settlement of shallow foundations. The accuracy of the method is sufficient to provide a basis for making an engineering decision regarding whether or not corrective action is warranted. It is possible to estimate the compressibility of soils without taking undisturbed samples and performing a consolidation test. Empirical correlations which relate the compression index to grain size (soil type) and percent compaction (density) can be made. It is, therefore, possible to determine some characteristics such as grain size and density of the backfill and evaluate the compressibility.

Table II gives a rough estimation of the compression index (C_c) based on the type of soil (seven categories) and relative density or consistency (two limit values and an average one) (Terzaghi and Peck, 1967; Peck et al., 1974; Hough, 1969; Bally and Perlea, 1983; McCarthy, 1977).

For classification in the three density categories, the corresponding void ratio or percent standard Proctor are given in Tables III and IV. An approximate correspondence between void ratio and the results of the standard penetration tests, based also on data in literature, is given in Table V.

TABLE II. Classification of Soil Types and Their Characteristics

Category of Soil	Type of Soil	ASTM D 2487 Class	Average C_c Values For: Loose/ Soft Material	Medium Dense	Dense/ Stiff Material
I	Gravel	GW GP	0.03	0.01	0.003
II	Silty/ Clayey Gravel	GM GC	0.05	0.02	0.008
III	Well Graded Sand	SW	0.06	0.02	0.007
IV	Poorly Graded Sand	SP	0.05	0.03	0.018
V	Silty Sand, Clayey Sand	SM SC	0.33	0.20	0.10
VI	Silty Soils	ML MH	0.40 or based on W_L as below	0.25	0.10
VII	Clayey Soils	CL CH	0.60* or $(W_L-10) \times 0.012$	0.40* or $(W_L-10) \times 0.008$	0.20* or $(W_L-10) \times 0.006$

*Values to be used if liquid limit (W_L) is not known.

TABLE III. State of Density Estimation When (Indirect) Measurements of Void Ratio are Available

Category of Soil	Type of Soil	ASTM D 2487 Class	Void Ratio Corresponding to Loose/ Soft Material	Medium	Dense/ Stiff Material
I&II	Gravels	GW GP GM GC	0.6	0.5	0.4
III&IV	Sands	SW SP	0.7	0.6	0.4
V	Silty/ Clayey Sand	SM SC	0.8	0.7	0.5
VI	Silty Soils	ML MH	0.9	0.75	0.5
VIIa	Clayey Soils (W_L<50)	CL CH	1.0 (1.2)*	0.8 (0.9)*	0.6
VIIb	Clayey Soils ($W_L \geq 50$)		1.6	1.1	

*Values to be used if liquid limit (W_L) is not known.

TABLE IV. State of Density Estimation Based on Known Degree of Compaction

Category of Soil	Degree of Compaction (Percent Standard Proctor - ASTM D 698-78) Corresponding to: Loose/Soft Material	Medium	Dense/Stiff Material
Any	80	90	100

TABLE V. State of Density Estimation Based on Standard Penetration Results

Category of Soil	Standard Penetration Blow Count, N, Corresponding to: Loose Material	Medium	Dense Material
Cohesionless Soils: I Through V	≤ 10	11-30	≥ 31
	Soft Material	Medium	Stiff Material
Cohesive Soils: VI	≤ 5	6-15	≥ 16
VII	≤ 5	6-10	≥ 11

As an alternate and for research purposes only, the state of density is estimated by the program MULTSPAN using some available correlations for standard penetration test as well as for cone penetration test and accepted relationship between static and standard penetrations (Fardis and Veneziano, 1981, Gibbs and Holtz, 1957, Marcuson and Bieganousky, 1977a and b, Perlea and Perlea, 1983, Schmertmann, 1970, Searle, 1979, Terzaghi and Peck, 1967), A general relationship was considered for estimation of the compressibility index (C_c):

$$C_c = C_{c,av} \times 10^{\frac{(A-B)\ (P-60)}{30}} \qquad (3)$$

Where:

A = $\log C_{c,av}$

B = $\log C_{c,w}$

$C_{c,av}$ = compressibility index of the soil in average condition, as given by Table II

$C_{c,w}$ = compressibility index of the soil in worst condition of density and moisture content, as given in Table II for loose/soft material.

P = a parameter representing relative density in cohesionless soils and consistency in cohesive soils: $30 \leq P \leq 90$.

Like $C_{c,av}$ and $C_{c,w}$, the parameter P is separately estimated for every type of soil, as shown in Table VI.

TABLE VI. Values of the Parameter "P" Used in the Estimation of Compressibility Index

Soil Category	P: If P > 90, do P = 90; If P < 30, do P = 30
I	$43 \times \log [96.56 \times N \times D_{50}^{-0.284} \times (\sigma'_v)^{-0.56}]$
II	$43 \times \log [72.42 \times N \times D_{50}^{-0.284} \times (\sigma'_v)^{-0.56}]$
III	$11.7 + 0.76 \sqrt{\lvert 222 \times N + 1600 - 0.368\, \sigma'_v - 50\, (C_u)^2 \rvert}$
IV	$21 \sqrt{N/(4.79 \times 10^{-4}\, \sigma'_v + 0.7)}$
V	$43 \times \log [36.21 \times N \times D_{50}^{-0.284} \times (\sigma'_v)^{-0.56}]$
VI	$43 \times \log [24.14 \times N \times D_{50}^{-0.284} \times (\sigma'_v)^{-0.56}]$
VII	$20 \sqrt{N}$

Notations used in Table VI have the following meaning:

N (blows/feet) - average Standard Penetration Test blow count for the range of depths critical for pipe deformation

D_{50} (mm) - mean diameter of particles

σ'_v (psf) - effective overburden pressure at the average depth of SPT measurements taken into account

C_u - coefficient of uniformity of the soil

Depending on the available information, soil density is estimated by the program MULTSPAN, less or more accurately, by interpolation in Tables III, IV, or V (or relationships in Table VI) and:

- from indirect determination of void ratio by nuclear measurements of soil density and moisture content,
- from design requirements or inspection records, which gives the degree of compaction; and
- from standard penetration tests.

Step No. 2 - Pressure Distribution Around the Structure

A method of estimation of the maximum horizontal pressure, P_h, exerted by the structure on the surrounding fill and the width and the distribution (rectangular, parabolic, or trapezoidal depending on the shape of the structure) of this pressure must be considered (see Figure 2).

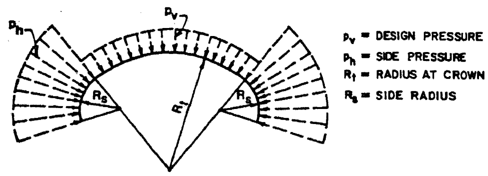

Fig. 2 Simplified Hypothesis for Stresses Around the Pipe

An usual approximation for an eliptical shape structure relates p_h to the vertical exerted pressure, p_v, and the ratio of top radius and side radius as follows (Watkins, 1975):

$$p_h = p_v \, R_t/R_s \tag{4}$$

The vertical pressure may be equated with the total overburden acting at the top of the structure.

<u>Step No. 3 - Horizontal Movement Calculation</u>

The classical theory of settlement for a shallow foundation may be used for calculating the horizontal movement. The fill at the side of the structure is considered as a soil column loaded by the pressure generated by the structure onto the fill. Generally, the decreasing of the induced stresses with the distance from the structure must be considered. This may be done using influence charts available for different distributions of the applied stresses (e.g. Fig. 3).

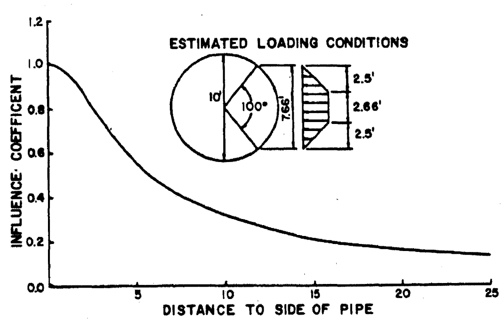

Fig. 3 Stress Distribution in Backfill

If the width of the backfill is small by comparison with the dimensions of the structure (e.g. smaller than the structure span dimension) a uniform distribution of stresses can be conservatively used (Fig. 4). If the width of the backfill is very large, the calculations can be limited to an influence distance of 2.5 rise dimensions.

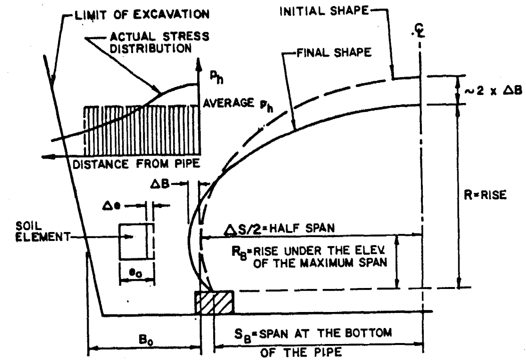

Fig. 4 Pipe - Backfill Interaction

The decrease in void ratio at a given distance from the structure may be estimated by the formula:

$$\Delta e = C_c \log \left[(K_o \, p_v + p_h)/K_o \, p_v \right] \tag{5}$$

Where:

- p_h = the supplementary pressure induced by the structure at a given distance from the structure.
- p_v = the effective overburden pressure at the level of calculation (in the middle of the loaded area by the structure; not at the top of the pipe).
- K_o = the coefficient of earth pressure at rest, which largely depends on the method and the intensity of compaction. (0.5 for natural deposits and 0.6 for compacted fills may be used as a rough approximation).

In an incremental layer of initial width B_o, for which the induced stress can be considered constant, the strain ΔB is:

$$\Delta B = B_o \times \Delta e/(1 + e_o) \tag{6}$$

Where e_o is the void ratio of the compacted fill not affected by the supplementary pressure induced by the structure; however, if the structure has already begun to deform, the void ratio may be less in the zone of influence of the structure.

Finally, the total horizontal displacement is converted into vertical movement of the pipe crown. For circular or quasi-circular pipes a good approximation is that the vertical movement is equal to the sum of horizontal movements on each side of the pipe. For pipes which significantly differ from the circular shape, a corrective shape factor is applied, as shown in Equation 2.

SOIL EVALUATION - CASE HISTORIES

The previously presented three-step method of calculating structure movement has been applied to many structures including several ODOT structures with predicted results being very close to actual measured deflections. Some case histories demonstrating the use of the soil evaluation analytical program to predict the structure movement are presented in what follows.

Table VII summarizes the results obtained by the use of the proposed method in some cases for which actual measured values were available. Data obtained from borings and nuclear density/moisture content measurements have ben used.

TABLE VII. Field Measurements of Crown Settlement and Computed Values

Structure No.	Soil Category in Backfill	Soil Category in Original Soil	Measured Vertical Movement (ft)	Computed Movement (ft)
DEL-37	I	VII	0.91	1.17
BUT-129	IV	VII	0.13[a]	0.57
BRO-62	V	Old Bridge Abutments	0.82	0.82
OKL-25	VII	Rock	0.94	1.00
OKL-78	VII	Rock	1.39	1.22

[a]The measured settlement is suspect since some difficulty was experienced in locating the original bench mark established during erection.

The good agreement between measured and computed movements is partially due to the fact that these case histories were used to evaluate parameters used in the proposed method. More experience is necessary (and probably further adjustment of the parameters) before the method may be used in pipe rating. Until then, only a rough approximation (an order of magnitude) of the deformation of the pipe is expected.

CONCLUSIONS

It can be seen from the above case histories that the simplified method gives very close correlation with actual measured deflections. The example cases have been demonstrated in a research program for the Ohio Department of Transportation. The method offers a simplified procedure for estimating deflection of corrugated metal pipes for a wider range of soil conditions and types. It can be used with initial (during construction) soil compaction data to estimate future deflection or to analyze the additional movement expected in spans already experiencing deflections. The authors have developed a method to rate a structure based on this method. This method uses the same rating system as the Bridge Inventory and Inspection Program.

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