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Maintenance of the Highway Infrastructure

Low Maintenance Bridges of Short Span

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ABSTRACT

This paper discusses two alternatives to conventional short span bridges with particular reference to Saudi Arabia, which require little or no maintenance during their service life. One particular example is that of soil-steel bridges which consist of shells of corrugated steel plate embedded in envelopes of engineered soil. Soil-steel structures, being substantially cheaper than their conventional counterparts, are frequently used in North America with good results not only for culverts but also for grade separations. The success or failure of a soil-steel structure depends upon the quality of the backfill (which should comprise well-graded granular material) and its degree of compaction (which can be easily achieved through unskilled labour but skilled supervision). A well-constructed soil-steel structure is expected to be virtually maintenance free in the environment of most of Saudi Arabia. This paper discusses the mechanics of behaviour and the methods of design and construction of soil-steel bridges. A specific example of a recently constructed structure with a span of about 18 m (which is believed to be the largest in the world) is presented.

Another low-maintenance structure, namely the buried Polyethylene pipe is also discussed.

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1/ INTRODUCTION

The raison d'etre for a highway bridge is the highway traffic which has to be got across the opening that the structure bridges. It is, therefore, appropriate that the design of the bridge be mainly governed by heavy vehicles which the bridge is expected to sustain during its life time. Paradoxically, however, the heavy vehicles have a relatively small influence on the periodic damage that a bridge receives. This periodic damage, which is repaired by routine maintenance, is caused mainly by environmental effects.

Since the maintenance of bridges is closely related to the environment, the discussion on low maintenance bridges can be dealt with only with reference to a particular environment. This paper deals with bridges in an environment which is similar to that in Saudi Arabia. It is assumed that the environment in Saudi Arabia is generally hostile to conventional reinforced concrete and prestress concrete bridges. It is further assumed that a good quality granular material is in abundant supply.

To restrain the length of the paper, its scope is limited to short span bridges, i.e. those with spans of less than about 20 m.

2/ SOIL-STEEL BRIDGES

A soil-steel bridge is made mainly with two components, namely a shell of corrugated steel plates and an envelope of well compacted granular soil. The metallic shell, which seems to provide a lining in the conduit through an embankment, is made up of bolted corrugated steel plates with annular corrugations. Plates with hellical corrugations are used for small diameter pipes. The rather simple-to-construct structure derives its strength from a complex interaction between the shell and the soil envelopes.

Since steel is the only material that has to be imported for its construction, a soil-steel bridge should prove to be an economical structure in a country like Saudi Arabia. It is an added advantage that this structure is also likely to be a low maintenance structure in the environment of the country.

The anatomy of a soil-steel bridge is shown in Figure 1 together with the definitions of some of the commonly used terms.

2.1/ Mechanics of Structural Behaviour

The bare metallic shell of a soil-steel bridge is extremely flexible. It is obvious that even under small loads, the shell would undergo large deformations. However, if the shell is surrounded by well compacted soil, the applied vehicle loads will reach the shell as radial pressures. In a perfectly round conduit with uniform radial pressure, the shell is subjected to only compressive forces. In an actual soil-steel structure, neither the cross-section is perfectly round, nor pressures radial and uniform. This gives rise to bending moments in addition to the compressive forces. Since the shell is flexurally weak, the bending moments may be large enough to cause plastic hinges to be developed at the crown and shoulders of the cross-section. Such plastic hinges, however, do not impair the load carrying capacity of the shell.

The bending moments in spite of being large enough to cause the development of plastic hinges in the shell, are still too small in magnitude to have a substantial effect on the capacity of the shell to sustain axial forces. Therefore, it is customary to ignore bending moments in the steel shell (see, for example, the Ontario Highway Bridge Design Code, 1983).

The backfill material performs seemingly two opposite roles. On the one hand it induces most of the load effects in the steel shell, and on the other, it provides the lateral support to the steel shell to enable it to carry fairly high axial forces.

The dead load supported by the shell is affected by soil-arching. If the shell has to sustain all the weight of the soil column directly above the conduit, then there prevails the condition of no arching. In this case, as shown in Figure 2, the thrust in the shell is equal to half the weight of the column of soil contained between two vertical planes passing through the springlines.

The degree of arching is affected mainly by the relative vertical movements of the columns of soil adjacent to and above the conduit. To illustrate the mechanics of this behaviour, an analogy is drawn between the soil-steel bridge and three interconnected loads resting on individual springs, with the middle load representing the column of soil above the conduit and the two outer loads representing the columns of soil adjacent to the conduit. It can be readily seen that if the middle load deflects more than the other two loads, a part of the middle load will be carried by the two outer springs, thus relieving the middle spring of some of its load. In terms of an actual structure, the downward relative movement of the column of soil above the conduit, tends to reduce the vertical soil pressure above the conduit as shown in Figure 3. This reduced soil pressure results in positive arching, and consequently reduced load effects in the steel shell.

2.2/ Design Procedures

The design of a soil-steel bridge has two main steps, namely the determination of dead and live load thrust in the metallic shell, and the calculation of the capacity of the shell to withstand this thrust.

The limit state design procedure as specified in the Ontario code (1983) is given in the following for a soil-steel bridge in which the metallic shell consists of the customary 152 x 51 mm corrugated steel plates, and the backfill comprises well compacted granular backfill.

The dead load thrust, T_D, can be obtained the following simplified method:

$$T_D = \mu_1 \ \sigma_{vo} \ R_t \qquad (1)$$

where σ_{vo} is the freefield overburden pressure at the crown level (i.e. the pressure which corresponds to the no arching condition), R_t is the radius of curvature of the shell at the crown and μ_1 is a dimensionless coefficient which depends upon the shape of the conduit and the depth of cover. The value of μ_1, can be read from the chart given in Figure 4 for well compacted granular backfill. The chart was developed from results of rigorous analyses by the Finite Element method.

The live load thrust, T_L, which is also assumed to be uniform around the conduit is given by:

$$T_L = 0.5(\text{lesser of } D_H \text{ and } \ell_t) \ \sigma_L \ (1+I) \qquad (2)$$

where, σ_L the equivalent uniformly distributed load at the crown level, is obtained by placing the two axle tandem, or a single heavy axle of the design vehicle centrally above the crown at the embankment level and distributing it through the fill at a slope of 1:1 in the transverse direction of the conduit and at a slope of 2 vertically to 1 horizontally in the direction of the conduit axis; D_H is the span of the conduit, ℓ_t is the length of the distributed load in the transverse direction of the conduit; and I is the dynamic load allowance. I is specified to be equal to 0.1 for depths of cover larger than 1.8 m. The simplified method for obtaining live load thrusts is based upon results of field testing (Bakht, 1981).

Following the limit state format of the Code, the buckling stress, f_b, of the metallic shell is required to satisfy the following relationship:

$$\phi f_b \geqslant (\alpha_D T_D + \alpha_L T_L)/A \tag{3}$$

The performance factor, ϕ, is specified to be 0.80 for structures with R_t less than 4.0 m, and 0.75 for structures with larger R_t. α_D and α_L are the dead and live load factors, and are specified to be equal to 1.25 and 1.40 respectively. A is the area of cross-section of the shell per unit length.

It is noted that all the quantities should be in consistent set of units.

The unfactored buckling stress, f_b, depends upon the radius of gyration, r, of the shell and the support provided by the backfill; it is given by:

$$f_b = f_y - \left(\frac{f_y^2}{12E}\right)\left(\frac{KR}{r}\right)^2 \frac{1}{\rho} \quad \text{for } R \leqslant \bar{R} \tag{4}$$

$$f_b = \frac{3E\rho}{\left(\frac{KR}{r}\right)^2} \quad \text{for } R > \bar{R} \tag{5}$$

where R is the radius of curvature of the segment under consideration, and $\bar{R}$ is an equivalent radius which is given by:

$$\bar{R} = \frac{r}{K}\left(\frac{6E\rho}{f_y}\right)^{0.5} \tag{6}$$

The factor K depends upon the flexural rigidity, EI_s, of the shell and stiffness of the support, and is given by

$$K = \lambda\left(\frac{EI_s}{ER^3}\right)^{0.25} \tag{7}$$

where $\lambda = 1.22$ for circular arches with rise-to-span ratios of less than 0.4 and for side and bottom portions of structures of other shapes. For the upper portions of the shell in all other structures, except above mentioned circular arches, the value of λ is obtained by the following expression

$$\lambda = 1.22 \left[1.0 + 2\left(\frac{EI_s}{\bar{E}R_t^3}\right)^{0.25}\right] \tag{8}$$

$\bar{E}$ is the modified modulus of soil reaction, and is given by

$$\bar{E} = E'\left[1 - \left(\frac{R_t}{R_t + H}\right)^2\right] \tag{9}$$

where H is the depth of cover.

ρ is the reduction factor for buckling stress.

$\rho = 1.0$ for $\left(\frac{H}{2R_t}\right) > 1.0$, $= \left(\frac{H}{R_t}\right)^{0.5}$ for $\left(\frac{H}{2R_t}\right) < 1.0$

For determination of E', soils are classified into three groups as shown in Table 1, and the proposed values of E' for soils compacted to different degrees are given in Table 2.

The strength of seams along the conduit axis is governed by the following equation

$$\phi S_s = \alpha_D T_D + \alpha_L T_L \tag{10}$$

In this case $\phi = 0.7$, and the value of S_s is obtained from Figure 5 which is based on test data.

2.3/ Construction and Installation

Construction and installation procedures have a profound influence on the success or failure of a soil-steel bridge. While the structure can withstand slight errors in structural design, any deficiences in construction procedures can have catastrophic results.

Briefly, the backfill should consist of well compacted good quality granular material. The compaction should be done in layers not exceeding 300 mm, on both sides of the conduit in such a manner that the difference in the levels of the backfill on the two sides at any transverse section does not exceed 600 mm. The well compacted granular backfill should extend at least half the span on each side beyond the springline.

The free movement of the crown during the backfilling operation must not be restricted by props or other supports. The upwards movement of the crown during the early stages of the backfill should be controlled by compaction pressure or by placing soil above the crown, so that the shell material is not stressed beyond yield.

The maximum depth of cover over the conduit wall should be the larger of $(D_H/6)(D_H/D_V)^{0.5}$ and 0.6 $(D_H/D_V)^2$ metres with a minimum of 0.6 m.

It is emphasized that while the erection of the shell and the compaction of the backfill can be carried out by relatively unskilled labour, it is absolutely essential that the supervisor of construction be an experienced person who is well acquainted with the construction of soil-steel bridges. Further details of proper construction procedures are given by Mirza and Porter (1981).

2.4/ Durability

All metal plates and appendages in a soil-steel structure are hot dip galvanized. The protective zinc coating, however, is not always fully effective in stopping the corrosion of the metal in certain environments.

Soil and water with low pH values and/or low soil resistivity are identified as being hostile to galvanized plates (Webster, 1963; Noyce and Richtie, 1979). Organic reducing soils are also found to be a major factor responsible for the corrosion of metal culverts.

Beaton and Stratfull (1959) indicate that inorganic oxidizing soils, containing less than 50% vegetation cover with the vegetation disintetrated by oxidation or by the process of drying, may be least hostile to galvanized steel.

It appears that the environment of Saudi Arabia, especially in areas remote from coastal areas, may be ideally suited to soil-steel bridges. In the absence of metal corrosion, the only maintenance that the structure would need is the repairing of the embankment slopes. Therefore, a soil-steel structure can be justifiably called a low-maintenance bridge in Saudi Arabia.

Before indiscriminately adopting soil-steel bridges in Saudi Arabia, it is appropriate to carry out a brief study on the corrosive effects of the country's environment on the galvanized steel shell of the proposed type of structure. Such a study, which can be conducted in a relatively short time, may even consist of merely the inspection of existing soil-steel culverts in the country.

3/ POLYETHYLENE PIPES

Generically speaking, buried polyethylene pipes are similar to soil-steel bridges with the difference that the shell of the former is made of polyethylene. The mechanics of soil and shell interaction is the same in the two structures. Polyethylene pipes are, however, not as large as soil-steel bridges can be. Spans of up to 2.0 metres have been successfully bridged by these pipes.

Polyethylene being more inert than galvanized steel, is more resistant to most chemicals and corrosive soils. The polyethylene pipe embedded in engineered soil may prove to be the low maintenance structure in certain locations in Saudi Arabia where the discharge consists of corrosive chemicals.

The cross-section of a polyethylene pipe can be custom changed for every installation. The basic cross-section is a flat one to which tubular cross-sections can be added to any pitch and in as many layers as required. Some possible cross-sections of the pipe are shown in Figure 6. Further details on this type of structure are given by Taprogge (1981).

Figure 7 shows the photograph of a polyethylene pipe which was used for a culvert under a major highway in Trinidad.

As can be seen in the Figure, a fairly long segment of the pipe together with the shafts for manholes can be assembled in the factory. Because of its relatively light weight and large handling strength, the pipe can be easily transported to the site. The construction procedure for this type of structure should be similar to the earlier described procedure for soil-steel bridges. The same design method as that for soil-steel bridges can also be used for buried polyethylene pipes with only minor modifications.

4/ AN EXAMPLE

A soil-steel structure with a record span of 18.0 m has recently been completed in Ontario. Figure 8 shows the structure during construction. The steel shell of the structure is made of 7 mm thick corrugated steel plates. The top portion of the shell is reinforced with closely spaced transverse ribs made out of steel I-beams, and the patented concrete beams running on each side of the conduit in the shoulder areas. The ends of the transverse ribs are encased in these beams.

The steel shell is supported on concrete footings. The rise of the structure is 7.32 m, and the length of the shell about 45 m. A total of about 86 tonnes of corrugated plate and 21 tonnes of transverse ribs were used in the bridge. It is estimated that this structure was about 20% cheaper than a conventional bridge.

This structure bridges over a stream. However, in many places, a soil-steel bridge has also been used in Ontario for grade separations.

5/ CONCLUSIONS

It has been shown that in Saudi Arabia, due to the abundant supply of granular material, the soil-steel bridge should prove to be an economical alternative to conventional short span bridges. This type of structure should also require low maintenance in the environment of the country. It is also shown that where the discharge comprises corrosive materials, a polyethylene pipe may prove to be the appropriate alternative for culverts with spans up to 2.0 m.

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Table 1/ Soil Classification for E'

Soil Group Number	Grain Size	Soil Types included	Unified Soil Classification Symbol*
I	Coarse	Well graded gravel or sandy gravel	GW
		Poorly graded gravel or sandy gravel	GP
		Well graded sand or gravelly sand	SW
		Poorly graded sand or gravelly sand	SP
		Granular 'A' soil**	GW, SW
		Granular 'B' soil**	SW, SP
II	Medium	Clayey gravel or clayey-sandy gravel	GC
		Clayey sand or clayey gravelly sand	SC
		Silty sand or silty gravelly sand	SM
III	Fine	Silts, sandy silts or plastic silts.	ML
		Lean clays, clayey silts.	CL

* According to ASTM D 2487-69
**According to MTC form 1010.

Table 2/ Values of E' for Various Soils

Soil Group Number*	State of Compaction	Standard Proctor Density**	Modulus of Soil Reaction, E', MPa
I	Loose	Less than 85%	6.5
	Medium	Between 85% and 95%	13.0
	Dense	Greater than 95%	20.0
II	Loose	Less than 85%	4.0
	Medium	Between 85% and 95%	9.0
	Dense	Greater than 95%	2.0
III	Loose	Less than 85%	1.4
	Medium	Between 85% and 95%	1.7
	Dense	Greater than 95%	2.0

* From Table 1.
**According to ASTM D698-70

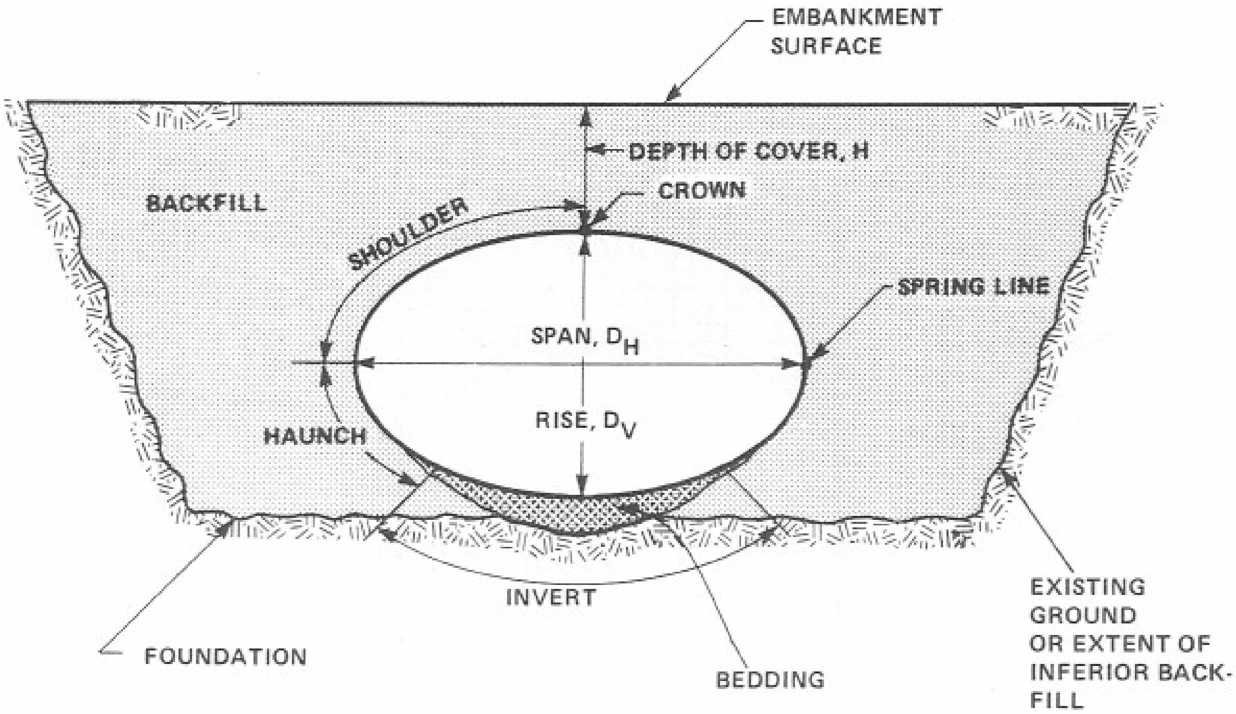

Figure 1/ Terminology used in Soil-Steel Bridges

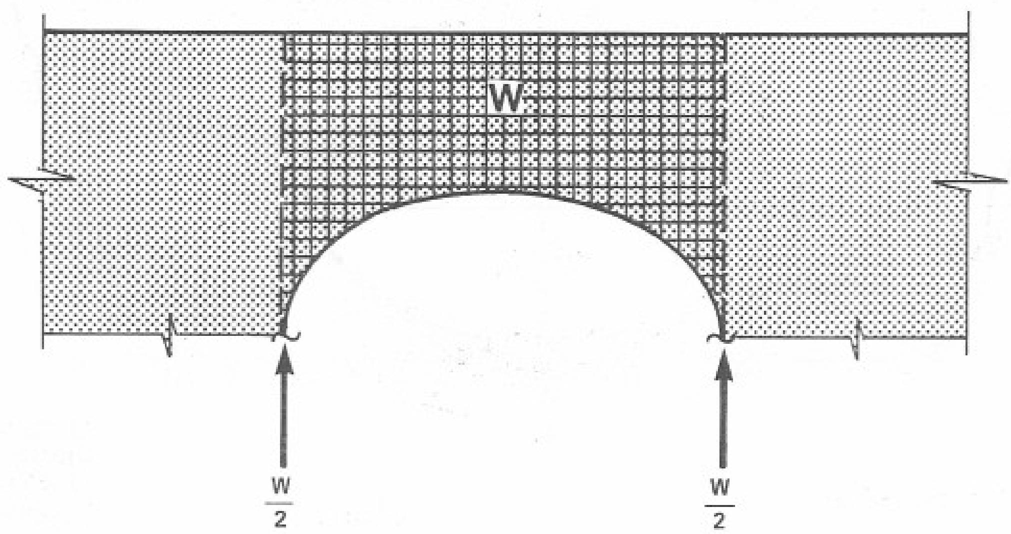

Figure 2/ No Arching Condition

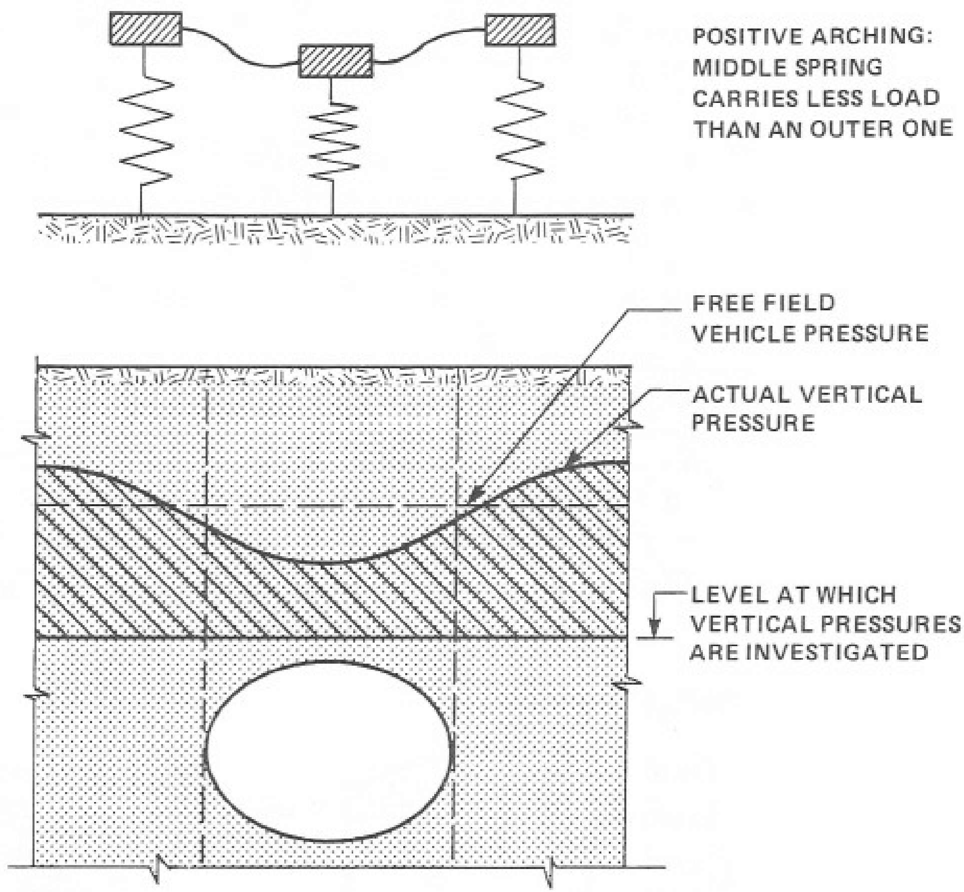

Figure 3/ Spring Analogy Showing a Positive Arching Condition

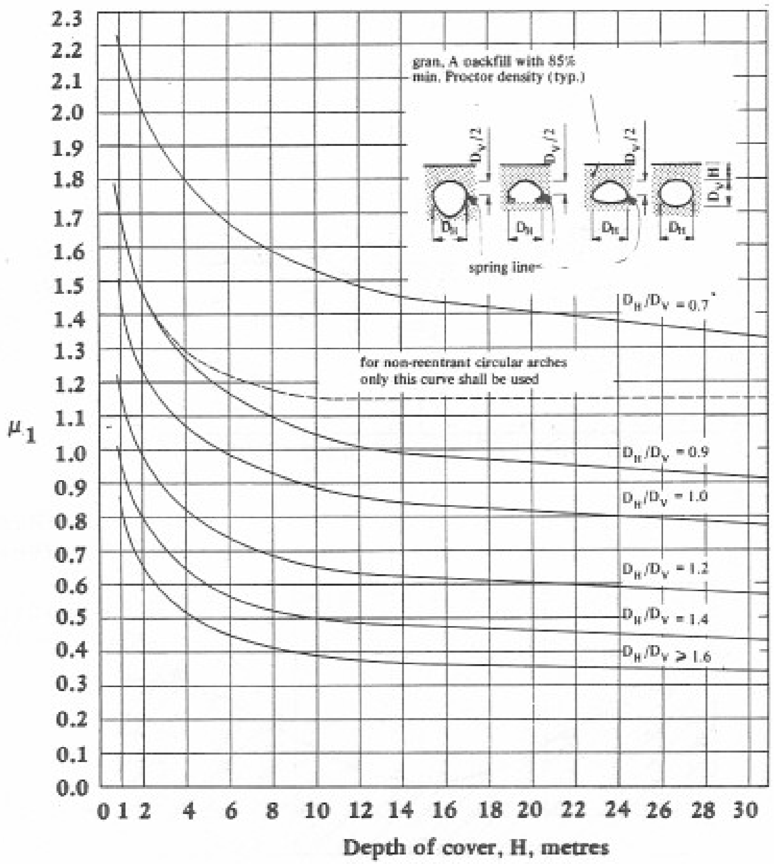

Figure 4/ Chart for μ_1

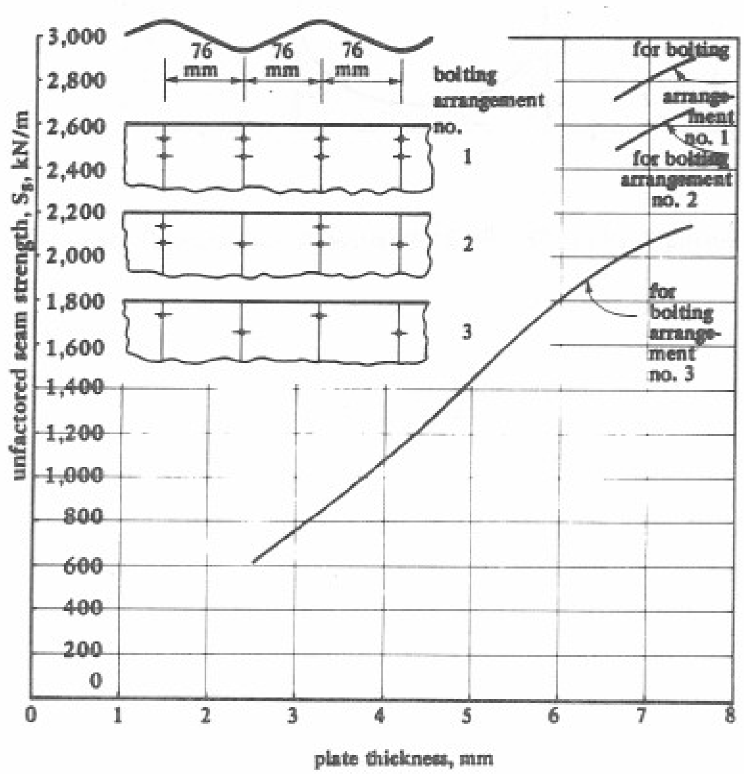

Figure 5/ Seam Strengths of Bolted Plates with 19 mm Diameter Bolts

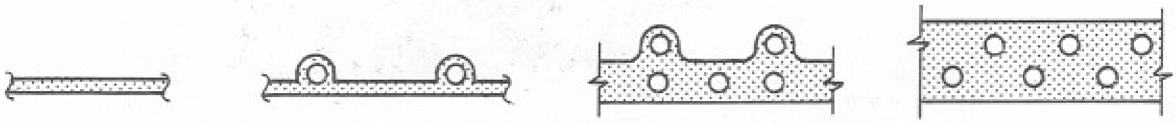

Figure 6/ Some Possible Wall Sections of Polyethylene Pipes

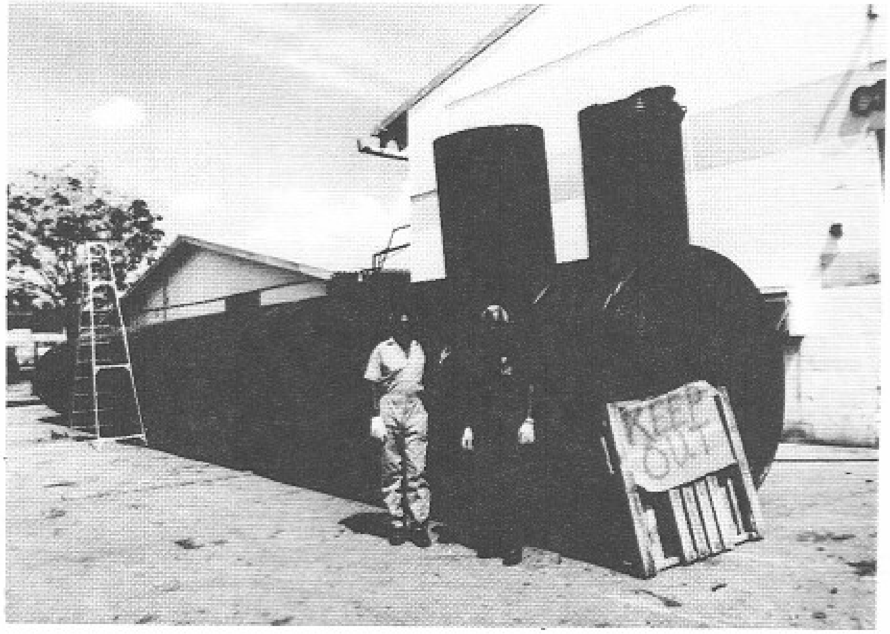

Figure 7/ A Polyethylene Pipe for Use in a Culvert in Trinidad, Manufactured by Century Eslon Ltd., Trinidad

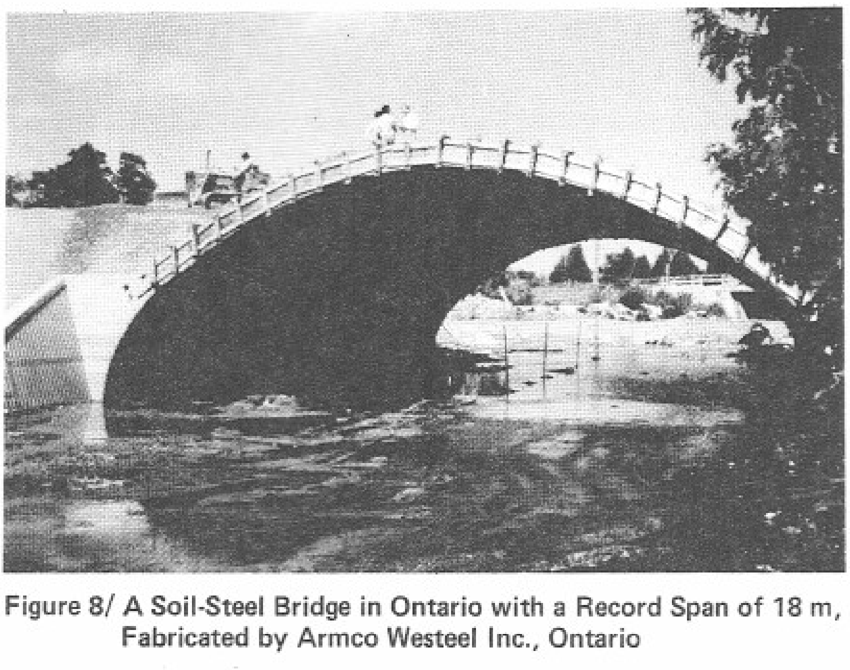

Figure 8/ A Soil-Steel Bridge in Ontario with a Record Span of 18 m, Fabricated by Armco Westeel Inc., Ontario