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Enhancement of the Uplift Capacity of Buried Pipelines by the Use of Geogrids

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ABSTRACT: The paper presents the results of preliminary tests that were conducted to investigate the possible use of geogrids for increasing the uplift resistance of buried pipelines. The results of the preliminary experimental investigations suggest that the uplift capacity of a pipeline section can be increased quite significantly by the incorporation of geogrids at the crown region of the pipeline in an advantageous and practicable configuration.

KEYWORDS: pipelines, uplift capacity, geogrid reinforcement, ultimate capacity, experiments, anchoring action

Buried pipelines are used quite extensively to transport materials such as oil and natural gas, coal slurries, mine tailings, and water. In contrast to above ground pipelines, the geotechnical design of the buried pipeline should take into consideration the mutual interaction between the pipeline and the surrounding soil. Such interactions can be induced by effects of external loads such as traffic and earth embankments, ground movement induced by frost heave, ground faulting and ground swelling, and inundation of the terrain. Accounts of recent developments in the area of soil-pipeline interaction are given by Ariman et al. [*1*], ASCE [*2*], Pickell [*3*], Selvadurai et al. [*4*], Jeyapalan [*5*], and Selvadurai [*6*]. Studies in this area focus on both the assessment of the flexural interaction response of the pipeline and on the estimation of the limiting resistance offered by the soil in the soil-pipeline interaction process.

In this study we shall focus on the type of problem in which the pipeline or a section of a pipeline is subjected to uplift deformations or loads during the interaction process. Such uplift action can take place as a result of inundation of the soil particularly in the early stages of the construction of a pipeline. Similarly, uplift of the pipeline can be induced at vertical transition zones particularly in situations where the pipeline experiences thermal or pressure induced expansion or thrust at overbends (Fig. 1). The uplift capacity of a pipeline can be increased in a variety of ways; these include the incorporation of weights (concrete sleeves) or mechanical anchors at discrete locations of the pipeline and the provision of an increased height of backfill over regions prone to uplift. While these are very useful techniques for increasing the uplift capacity of a pipeline they tend to be both time consuming and expensive construction procedures.

In the geotechnical evaluation of the soil-pipeline interaction at regions that are subject to uplift, it is of course necessary to evaluate the manner in which the soil provides the necessary resistance to the uplift loads. The subject of uplift behavior of pipe sections that are located in granular soil media have been investigated by Matyas and Davis [*7,8*], and Trautmann et al. [*9*]. Similarly, the lateral or horizontal capacity of pipe sections have been investigated by Audibert and Nyman [*10*] and Trautmann and O'Rourke [*11*]. The articles also contain comprehensive lists of references associated with this aspect of evaluation of the load-displacement behavior of buried pipelines. In a majority of these investigations the weight and shearing of the soil mass provides the primary resistance to failure. Since the increase of the ultimate uplift (or lateral) resistance is of crucial importance in both the efficiency and long-term performance of the buried pipeline, it is natural to enquire whether these resistances can be increased by the provision of an efficient and economical mode of reinforcement.

This paper investigates the application of geogrid [*12*] reinforcements for enhancing the uplift resistance of buried pipelines. Geogrids have been used quite effectively to improve the load carrying capacity of soils in a number of geotechnical applications. These applications include soil improvement beneath level ground and inclined slopes, pavement structures, earth retaining structures, and earth embankments [*13-15*]. In the present work, a catalogue of experiments were conducted to evaluate the efficiency of geogrids in enhancing the uplift capacity of a pipeline section that is embedded in a granular soil mass. The paper describes the experimental procedure and summarizes the results of a series of preliminary tests that were conducted to assess the increase in the uplift capacity of the pipeline caused by the presence of the geogrid.

The Experimental Facility

The program of experiments was designed to evaluate the uplift capacity of a section of pipeline inducing a state of two-dimensional plane strain in the soil medium. The experiments were performed in a concrete test container with the following inside dimensions: 1500 mm in length, 880 mm in width, and 1200 mm in depth. The wall thicknesses of the test facility were approximately 150 mm (Fig. 2). The larger sides of the test facility were lined with highly polished stainless steel surfaces. The pipe section used in the investigation was approximately 150 mm in diameter and approximately 850 mm in length. The clearance of approximately 15 mm

Note: Discussion is encouraged and should be submitted by March 1, 1990.

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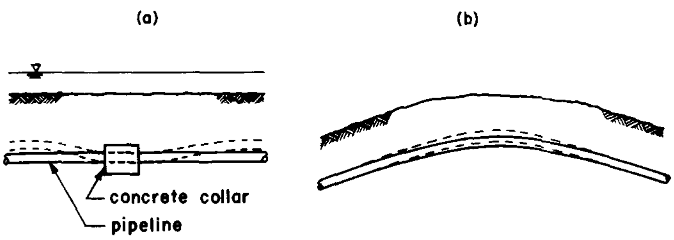

FIG. 1—*Uplift action in buried pipelines:* (a) *effects of a floatation force and* (b) *overbend thrust caused by thermal or pressure effects.*

between the flat end surfaces of the pipe and the stainless steel sides of the test facility was to ensure that no frictional tractions would develop at the ends of the pipe. In order to prevent the soil becoming lodged in this gap region, the plane end of the pipe and the test tank are fitted with layers of soft foam rubber. The pipe section is connected to a moving horizontal frame by two threaded rods (Fig. 2). The movement of the horizontal loading platform induces an upward pipe movement in a controlled and uniform fashion.

The loading platform is confined to move in a vertical direction by two roller bearings that exert virtually no frictional resistance. The controlled movement of the loading platform is achieved by an electrically driven motor-mechanical actuator combination. The rate of movement of the actuator is controlled by a variable power input. The loading devices are mounted on a reaction frame that is anchored to the base of the laboratory floor and the sides of the tank. A general view of the experimental arrangement is shown in Fig. 2. The uplift loads that are applied to the pipeline section are measured via a load cell, which is located between the actuator ram and the moving platform. The displacements of the moving platform are monitored by two LVDTs, which are located at its extreme ends. The load cell readings and the LVDT readings are monitored via a Hewlett Packard (HP) 3421A Data Acquisition System, and the data are recorded on a HP 9836 desk top computer. The software is written in such a way that the load-displacement behavior of the pipeline section can be monitored as the experiment progresses.

Experimental Procedure

The sand used in the experimental investigation can be described as a mortar sand with effective diameter $D_{10} = 0.27$ mm, coefficient of uniformity $C_u = 3$, and a coefficient of curvature $C_c = 0.95$. According to the Unified Soil Classification System the material can be described as a poorly graded sand (SP), gravelly sand with little or no fines. Throughout the experiments the moisture content of the sand was maintained between 4 to 5%. The bulk unit weight in a compacted state (used in the experimental programme) was approximately 17.5 kN/m^3. At an average moisture content of 4.5% and a bulk unit weight of 17.5 kN/m^3, the shear strength parameters approximately corresponded to an angle of internal friction of $\phi \approx 40°$. The bulk unit weight of 17.5 kN/m^3 approximately corresponded to a compactive effort consistent with the modified Proctor compaction procedure.

The experimental research program consisted of two distinct phases. In the first series of experiments the uplift capacity of the pipeline section was determined in the absence of the geogrid reinforcement. These tests were conducted for a single depth of embedment (600 mm), which corresponded to an embedment depth to pipe diameter ratio of 4. The experimental procedure in conducting these tests can be summarized as follows. The pipe section along with the loading rods are first removed, and an initial layer of sand is compacted to a depth of approximately 500 mm. This layer forms the base on which the pipe section could rest during the compaction of the remainder of the granular soil mass. The compactive effort is provided by a flat ended steel compactor measuring approximately 150 mm square and weighing 76 N. The layers are compacted in approximately 75-mm lifts, and the compactor has a free fall of approximately 150 mm. Each surface was compacted twice to ensure an even compaction. The pipe section was placed on the initially compacted layer and aligned to ensure correct ap-

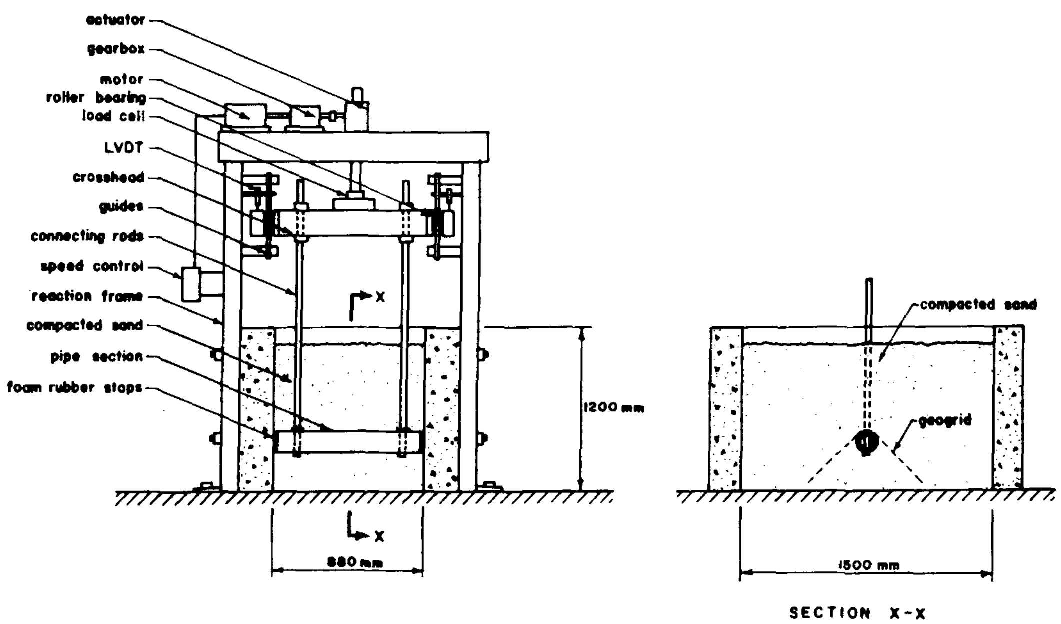

FIG. 2—*A schematic view of the test facility.*

plication of an axial uplift load. The loading rods were left unconnected throughout the compaction of the granular soil in the test tank. Once the soil layer was compacted to the desired depth the loading rods were connected to the loading platform. By maintaining the loose connection between the loading platform and the connecting rods it was possible to ensure that there was no preload accumulated in the system during the compaction procedure, and there was no premature failure of the soil as a result of any over compaction.

The second group of experiments incorporated the geogrid reinforcement. The procedure for the installation of the pipeline with geogrid reinforcement can be summarized in the following manner. The soil layer was initially compacted to a depth of approximately 500 mm. This compacted sand was partially excavated to form the trenches to receive the pipe section and the geogrid. The geometry of the trenches were organized in such a way that in its final position the geogrid would have a development length of approximately 350 mm, and it would be inclined at approximately 45° to the axis of loading. The pipe section was placed at the central ridge (Fig. 3), and the geogrid was placed over the crown level of the pipe section.

In the subsequent compaction procedure the soil is first compacted within the trench sections. Uniform layers of soil are subsequently placed and compacted using exactly the same procedures as outlined previously. Again the loading rods are maintained aligned but unsecured during the compaction procedure. When the soil is compacted to the required depth, the loading rods are rigidly connected to the loading platform. Since the loads are applied through an actuator system, the test is essentially displacement controlled. The rate of movement of the loading platform can be varied by a variable speed control of the driving motor. In the experiments conducted the rate of application of the loads corresponded to approximately 0.02 mm/s.

Experimental Results

Three experiments were conducted to determine the uplift load capacity of the pipe section that was embedded in the granular medium without provision of the geogrid reinforcement. The experimental results are shown in Fig. 4. Since standardized procedures were used for the compaction of the soil the test results displayed a good degree of repeatability in the load-displacement pattern. It may be noted that for the unreinforced embedded pipeline section the uplift load reaches a peak value, and as deformation progresses there is a reduction in the resistance to uplift loads. The decrease is appreciable, and the recorded maximum reduction is approximately 40%. Unloading-reloading excursions were also carried out in two of the experiments. A typical result is shown in Fig. 4. Three experiments were also conducted to determine the influence of the geogrid reinforcement on the uplift load-displacement characteristics of the embedded pipe section. Here again the results of the series of tests displayed marked similarities, and the results shown in Fig. 4 indicate the average values, and the range observed for the three tests. It is evident that the uplift load carrying capacity of the pipe section is greatly enhanced by the presence of the geogrid reinforcement. Furthermore the load-displacement results do not indicate any evidence of a strength reduction with increasing pipe deflections. The results of an unloading-reloading cycle also indicate that the reinforced system is capable of maintaining the load carrying capacity without appreciable reduction.

The number of variables investigated in these preliminary sets of experiments are rather limited, and as such it is not prudent to compare the experimental results with any theoretical estimates of the ultimate loads, which are based on either limit equilibrium solutions or numerical computations based on finite-element or boundary-element schemes. The latter techniques are of course needed to examine the influence of the geogrids particularly in view of the fact that no failure is observed in the geogrid during the attainment of the peak load corresponding to the reinforced case. The peak load can however be estimated, very approximately by appeal to the vast number of estimates that are derived from limit equilibrium calculations applicable to a strip anchor plate. It must however be noted that the wedge patterns for the failure of the soil caused by movement of the pipe can be different to those that may be observed in an anchor plate. Considering a simple wedge failure

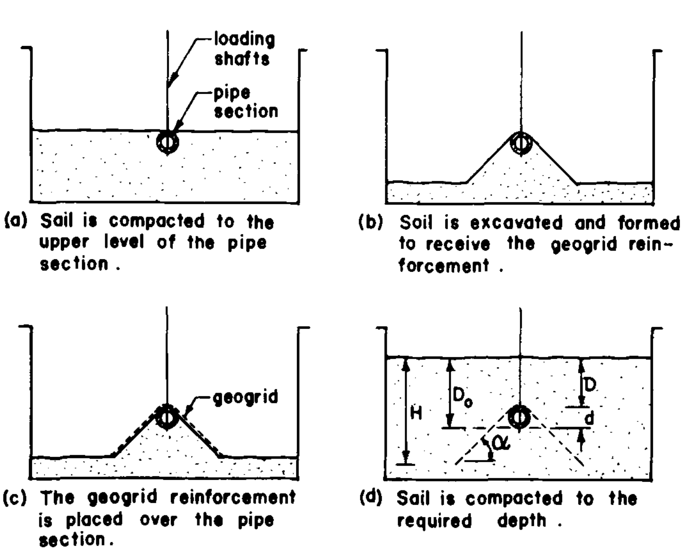

FIG. 3—*Procedure for the installation of the pipeline and geogrid reinforcement.*

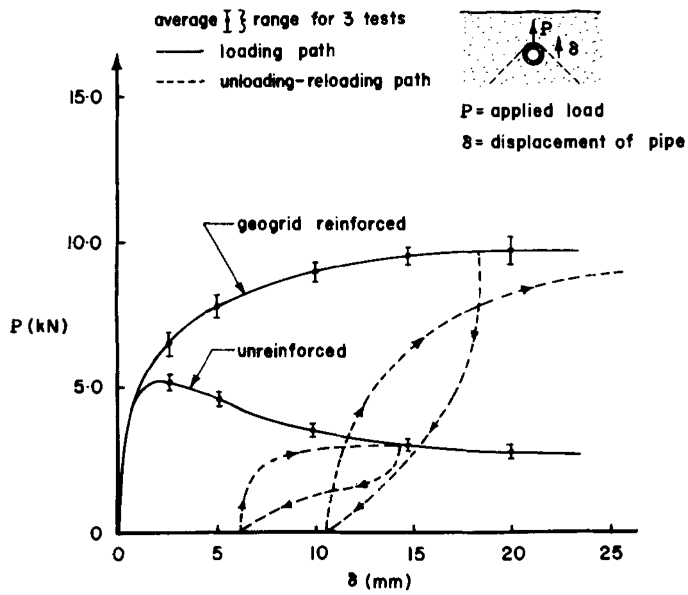

FIG. 4—*Load-displacement behavior for the pipe section subjected to uplift loads. The influence of geogrid reinforcement.*

concept it can be shown that [16] the ultimate load capacity of the pipe section for the unreinforced case can be expressed in the form

$$P_u = \gamma DdL\left\{1 + \frac{D}{d}K_u \tan\phi\right\} \qquad (1)$$

where d is the diameter of the pipe section, D is the depth of embedment, L is the length of the pipe section, γ is the bulk unit weight, and K_u is an earth pressure coefficient (Fig. 4 of Ref 16).

Ladanyi and Hoyaux [17] have presented a solution of the "trap-door" problem related to a granular medium, which can be utilized to estimate the ultimate load capacity of the buried pipe section. The limiting uplift load for the embedded pipe section can be written as

$$P_u = \gamma DdL\left(1 + \frac{D}{2d}\sin 2\phi\right) \qquad (2)$$

Das and Seeley [18] have proposed an alternative expression for estimating the uplift capacity of horizontal anchor plates embedded in granular soils. The experimentally based result for the uplift limit load can be written as

$$P_u = \gamma DdL\left\{\frac{D}{d}K_u \tan\phi\left[\left(2m\frac{D}{d} + 1\right)\frac{d}{L} + 1\right] + 1\right\} \qquad (3)$$

where the factor m is defined in Table II of Ref 16. For the pipeline problem examined in the paper where D = 600 mm; d = 150 mm; L = 880 mm; γ = 17.5 kN/m^3; ϕ = 40°, Eqs 1, 2, and 3, give ultimate limit loads of 5.84, 4.13, and 4.63 kN, respectively. The corresponding experimental value for the average ultimate limit load is approximately 5.1 kN.

When considering the effect of the geogrid reinforcement, a complete analysis should take into account the rather complex mechanical interactions that take place in the vicinity of the pipe section. These include the deformability characteristics of the reinforcement, failure of the soil mass, separation at the soil-pipe interface, and so forth. As a first approximation, the additional limiting resistance generated by the geogrid reinforcement can be calculated by examining the limiting equilibrium situation where complete failure at the soil-geogrid interface is generated. For this purpose we assume that the in-situ stress rate in the soil is given by $\sigma_1 = \gamma z$; $\sigma_3 = K_0\gamma z \simeq (1 - \sin\phi)\gamma z$ where z is the depth of the point of interest from the ground surface. Evaluating the limiting resistance mobilized by the geogrid reinforcement it can be shown that the additional uplift resistance generated by the geogrid takes the form

$$P_r = \gamma L(H^2 - D_0^2)[2 - \sin\phi(1 - \cos 2\alpha)]\tan\delta \qquad (4)$$

where H is the depth at which the geogrid is terminated, D_0 is the depth to the underside of the pipe, α is the inclination of the geogrid (Fig. 3), and δ is the effective angle of friction for reinforcement pull out. In order to evaluate Eq 4 it is necessary to determine the effective angle of friction δ. As has been observed by Ingold [19], Jewell et al. [20], and others, the effective friction angle is highly dependent on the normal stresses that act on the failure plane. Particularly at low normal stress levels ($<$20 kN/m^2) the dilatancy effects should be taken into consideration in the evaluation of δ. This can lead to δ being greater than the angle of internal friction ϕ for the soil. As the normal stress on the reinforcement plane increases, the effective angle of friction δ approaches ϕ. The result (Eq 4) also assumes that the frictional resistance in the geogrid is mobilized only in the soil region below the lower level of the pipe section. This will account for the loss of confinement in the soil adjacent to the pipe section during its movement. Furthermore it is assumed that the self weight stresses normal to the geogrid remain unaltered during the movement of the pipe section. In general, it may be noted that the processes that govern the generation of anchoring action in the geogrid are quite complex; the result Eq 4 is a highly simplified treatment of the limiting equilibrium situation. In the experimental investigation we have H = 1000 mm; D_0 = 0.75; α = 45°, and ϕ = 40°. As a conservative estimate, the effective friction angle for the geogrid pull-out is taken to be equal to the friction angle of the soil (that is, $\delta = \phi$). Considering these values we obtain P_r = 7.74 kN. This value of the ultimate uplift resistance generated by the geogrid has to be added to the resistance generated by the pipe to obtain the total uplift resistance for the case of the geogrid reinforced pipeline section. It may be noted that concomitant failure does not occur in the two systems (soil-pipe interaction and soil-geogrid interaction). As is evident from Fig. 4 the soil resistance experiences some degradation as the peak load is reached in the geogrid interaction. Assuming that there is no reduction in the peak value of the uplift resistance generated by the soil-pipe interaction, it is evident that the ultimate uplift resistance for the geogrid reinforced pipe section (that is, $P = P_r + P_u$) can range from 13.58, 11.87, and 12.37 kN consistent with estimates for P_u given by Eqs 1, 2, and 3, respectively. In the instance where the experimentally derived strength reduction in the unreinforced case is taken into consideration, we have $P \simeq$ 10.5 kN. This value can be compared with the experimental value of approximately 9.5 kN.

Conclusions

This paper discusses briefly the results of a series of preliminary experiments conducted to ascertain the influence of geogrid reinforcement on the uplift capacity of pipe sections that are embedded in compacted moist granular soils.

The results of the experimental investigations are sufficiently novel and encouraging to warrant further research. It is shown that the judicious incorporation of geogrids can lead to a substantial increase in the uplift capacity of the buried pipeline section. The results of the preliminary series of tests are, however, not all encompassing.

In a comprehensive experimental evaluation of the effectiveness of the application of geogrids a variety of factors need to be considered. These include the influence of (1) the depth/diameter ratio of the buried pipe section, (2) the surface characteristics of the pipe section (that is, rough versus smooth), (3) the length of the geogrid reinforcement, (4) the aperture size of the geogrid, (5) the inclination of the geogrid in relation to the direction of application of the uplift load, and (6) the degree of compaction of the backfill. A comprehensive experimental program that encompasses all these factors is currently in progress. These experimental investigations are complimented by a program of theoretical research based on use of nonlinear finite-element and boundary element techniques that model the various interaction features of the pipe section that is subjected to uplift loads. The results of the preliminary experiments conducted to date suggest the following:

1. The incorporation of geogrids can lead to a substantial increase in the uplift capacity of pipe sections.
2. When the peak loads are considered, the increase in the uplift capacity of the reinforced system can be of the order of 100%. It must of course be emphasized that this degree of enhancement in the uplift capacity is derived via an experimental scheme involving a pipe of single diameter. It is forseeable that as the diameter of the pipe increases the contribution from the geogrid will represent a smaller fraction of the uplift capacity of the reinforced system; the maximum capacity of the geogrid will be the governing factor.
3. The incorporation of the geogrid can lead to a system in which the increased uplift capacity can be maintained with increasing uplift displacements of the pipeline section; this is in contrast to the performance of the unreinforced system, which displays a certain degree of load reduction or softening beyond the peak load.
4. When considering the ultimate capacities corresponding to the large pipe displacements, the incorporation of geogrid reinforcement can lead to an increase of nearly 250% on the ultimate capacity.
5. The availability of this ductility in the system can be of great benefit to increasing and maintaining the uplift capacity of a pipeline at a vertical transition zone without the added cost of berm construction or the provision of anchors and concrete sleeves.
6. The incorporation of the geogrid in an actual pipeline construction situation merits further consideration. Figures 5 and 6 show a sequence of operations that can be used to place the geogrid, in a beneficial manner, during the installation of the pipe [*21*].

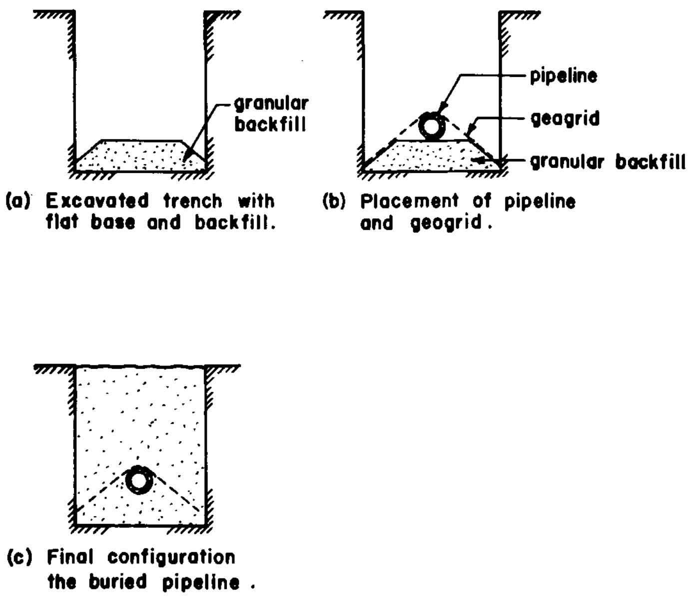

FIG. 5—*A procedure for the installation of the geogrid.*

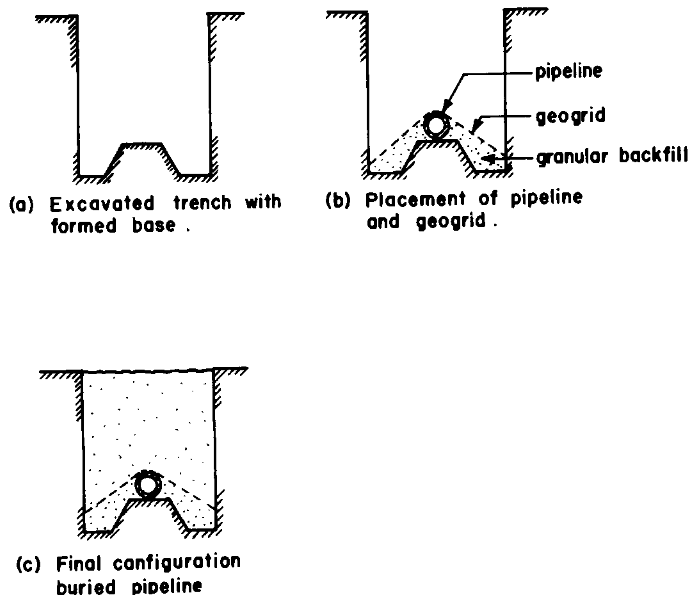

FIG. 6—*A procedure for the installation of the geogrid.*

Acknowledgments

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