STABILITY ANALYSIS FOR BURIED PIPES

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ABSTRACT

Ring instability is an impulsive deformation that progresses. At worst, instability is ring collapse. Buried pipes can invert only if the ring deflects and the soil slips at the same time. Instability of buried pipes is analyzed as a soil-structure interaction. Ring stiffness resists inversion; soil supports the ring to keep it close to circular shape.

The present paper demonstrates the basic manners of ring instability for buried flexible pipes, ring deformation and buckling at yield stress. The analysis found that if the pipe is to be subjected to vacuum it is very important to limit ring deflection to 5%. Because it increases the maximum vacuum to be larger than atmospheric pressure, therefore the pipe would not collapse.

If the pipe is so flexible ring stiffness cannot be support any of the soil load. With 8% ring deflection, the vacuum at collapse is, - 0.55 bar with neglect term, Ed/rn^3, for ring stiffness.

For the design of pipes to withstand internal vacuum, a safety factor of 1.5 is recommended. It is prudent to require that embedment soil be denser than critical. Critical density can be evaluated in the soils laboratory. Even without a water table, percolating water and earth tremors tend to shake loose soil do such that ring deflection could increase and reduce internal vacuum at collapse.

Keywords: Water Pipeline, Flexible Pipes, Stability Analysis.

INTRODUCTION

Collapse of buried flexible pipes is either, wall crushing or inversion. Collapse due to longitudinal bending is not included in this analysis. Bending deforms the pipe cross section into an ellipse with the short diameter in the plane of the bend. Following are procedures for evaluating the vacuum at which a buried flexible ring collapses. As ring could be held circular, so analysis would be simple ring compression. But flexible ring analysis predicts ring deflection, do, before the vacuum is applied. Ring deflection depends upon ring stiffness and stiffness of the embedment soil. It is assumed that pipes are initially circular and empty, and that coefficient of friction between the pipe and the backfill is zero because of the inevitable breakdown of shearing stresses due to changes in temperature, moisture, and pressures. The embedment is assumed to be granular. The flexible pipe is often assumed to be thin-thickness.

Performance limit is collapse which occurs if the ring either crushes due to ring compression, or inverts due to sidefill soil slip at B. The equation for Collapse by wall crushing, (Moser):

$$\sigma_f = \frac{(P+p)(1+d)OD}{2A} \tag{1}$$

where σ_f is ring compression stress at yield stress in the pipe wall at B, *A* is wall area per unit length of pipe, *T* is wall thickness, equal A for plain pipes, OD is outside diameter, *P* is external pressure at top of pipe, *p* is internal vacuum, *d* is ring deflection.

Area, *A*, is used for transformed composite sections, or ribbed, or ring-stiffened or corrugated. At ring deformation collapse the soil must slip in order for the ring to deflect. The vertical pressure includes soil pressure and vacuum; i.e. $P_A = P + p$. Before it is buried, the ring is circular, but as backfill is placed, the ring deflects into an ellipse. If the ring is flexible, and if shearing stresses between pipe and soil are negligible, vertical and horizontal soil pressures are related. Therefore, (Anderson):

$$P_B = P_A (1+\mathrm{d})^3 /(1-\mathrm{d})^3 = P_A r_r \tag{2}$$

where r_A is mean radius of curvature at the top A, r_B is mean radius of curvature at the side B, P_A is pressure on the pipe at A, P_B is pressure on the pipe at B, *d* is Δ/D = initial ring deflection, r_r is $(1+\mathrm{d})^3 /(1-\mathrm{d})^3$ which is ratio of radii.

But for any pipe stiffness, *F*/Δ (or equivalent ring stiffness, 53.77 EIID3), the ring itself is able to support part of the vertical pressure as it deflects.

STUDY APPROACH

Internal vacuum as a passive pressure should be added to external water pressure before making buckling analysis. Performance limit for internal vacuum is ring inversion. Critical vacuum *p*' is sensitive to the radius of curvature and reduced by ring deflection. If radius of curvature is less than vertical radius of curvature r_y. ring stiffness EI/r^3_y is less than EI/r^3 as deflected ring reduce vacuum at collapse.

It is the objective of the present work to demonstrate the influence on stability of different flexible pipes installed at different conditions, due to vacuum at collapse. Pipes investigated in this paper meet the requirements of such international standards as ASTM, AWWA, DIN, BS, and ISO. Pipes properties complying with those various national and international standards are based on long term data interpolated to

50 years.

An elementary knowledge of basic principles of soil stresses is essential to understanding the structural performance of buried pipes. These principles are explained in standard texts on soil mechanics. A few are reviewed in the following paragraphs because of their special application to buried pipes.

Vertical Soil Pressure

External soil pressures on the pipes must be known for the analysis and design of buried pipes. Vertical soil pressure at the top of the pipe is caused by dead load, d' the weight of soil at the top of the pipe, due to height of soil cover, *H*, and live load, P1, the effect of surface live loads at the top of the pipe. Vertical soil pressures at the top of the pipe are a functions of height of soil cover, *H*, for an HS = 20 truck axle load of 32 kips, and soil unit weight of. Soil unit weight can be modified. Also other factors must be considered. If a water table rises above the top of the pipe or the pipe deflects, or the soil is not compacted, or in excess of compacted.

If the embedment about a buried pipe is densely compacted, vertical soil pressure at the top of the pipe is reduced by arching action of the soil over the pipe, like a masonry arch, that helps to support the load. To be conservative, arching action is usually ignored. However, soil arching provides an added margin of safety. If the soil embedment is loose, vertical soil pressure at the top of the pipe may be increased by pressure concentrations due to the relatively uncompressible area within the ring in loose, compressible soil. Pressure concentrations due to loose embedment cannot be ignored. For design, either a pressure concentration factor is needed, or minimum soil density should be specified. Over along period of time, pressure concentrations on the pipe may be reduced by creep in the pipe wall (plastic pipes), earth vibrations, freeze-thaw cycles, wet-dry cycles, etc. The most rational soil load for design is vertical soil pressure at the top of the pipe due to dead weight of soil plus the effect of live load with a specification that the soil embedment be denser than critical void ratio. Critical void ratio, roughly 85% soil density (AASHTO T-99), is the void ratio at such density that the volume of the soil skeleton does not decrease due to disturbance of soil particles.

Total pressure is used to calculate ring compression stress. Inter granular soil pressure is used to calculate ring deflection which is a function of soil compression. As the soil is compressed, so is the pipe compressed and in direct ratio. But soil compression depends only on inter granular stresses. Failure of a buried pipe is generally associated with failure of the soil in which the pipe is buried.

Cohesion less Soil Failure, for most buried pipes, the embedment around the pipe is specified to be cohesion less soil such as sand or gravel. For cohesion less soil, $c = 0$ at soil friction angle φ. For most soil analyses, the principal stresses are horizontal or vertical. For analysis of failure of the embedment around a buried pipe, the relationship of the principal stresses, at soil slip becomes pertinent.

Cohesive Soil Failure

Under some circumstances, pipes are buried in cohesive soil such as clay. A saturated fat clay has a negligibly small friction angle φ, but does have significant cohesion c. of the Mohr circle. Vertical stress acts on a horizontal x-plane and the horizontal stress acts on a vertical y-plane. The shear planes (slip), are at O = 45°. However, failure in Cohesive is general shear; i.e., viscous or plastic flow.

For pressure against soil at spring lines, the horizontal pressure of the pipe against the soil at B is reduced by, (Moser):

$$Po = Ed \ / m^3 \qquad \text{i.e.,} \qquad P_B = P_A + P' - P_0)r_r - P$$

$$P_B = P_A + u_A + P' - Ed / m^3)r_r - P \tag{3}$$

where P_B is horizontal pressure of pipe on soil, P_A = vertical external soil pressure at A, p is internal vacuum, EI/D^3 is ring stiffness, $F / \Delta = 53.77(Ed / m^3)$ (pipe stiffness), D is mean diameter of the circular ring, R is mean radius of the circular ring (D/2), t is thickness of the plain pipe wall, m is r/t (ring flexibility), d is Δ/D is initial ring deflection, r_r $(1 + \mathrm{d})^3/(1 - \mathrm{d})^3$ is ratio of vertical and horizontal radii (maximum and minimum radii of the ellipse). If soil at B does not have adequate strength, the soil slips, and the ring inverts strength. Because most embedment is granular, the analysis of strength for granular (cohesionless) sidefill. The horizontal strength of soil at point B, at soil slip, is soil passive resistance, $\sigma x = K \sigma y$ where, $\overline{\sigma x}$ is horizontal effective soil stress at B, $\overline{\sigma_Y}$ is vertical effective soil stress at B, K is ratio of horizontal to vertical effective stresses at soil slip (ring collapse), $K = (1 + \sin\varphi)/(1 - \sin\varphi)$, φ is friction angle of the embedment, for which values can be obtained from tests.

Flexile pipes should be embedded in non-cohesive backfill materials such as medium sized gravel, crushed rock, sand, or sand/gravel mixtures because of the wide variability that can be achieved in cohesive soil's mechanical behavior (e.g. consolidation, shear strength, permeability, etc.) at different moisture contents.

In the present work the backfill was assumed to be buried in embedment of dry, uncompacted sand saturated with water table and soil cover H, 0.65m. Weight of the sand is 17,000 N/m^2. The soil friction angle is 25°. Ring deflection was not controlled during backfilling, so the average initial ring deflection is 8%.

Regarding the surface loading and internal vacuum pressure utilized in this paper. Table (1) presents the values of all these variables and pipe diameter, and pipe mechanical properties, as well.

Table (1): Values of the different variables in the present study

No.	Variable	Value
1	Nominal Diameter (mm)	1300
2	Ring stiffness, (KPa), EI/D^3	1.365
3	Maximum Vacuum (atmospheric pressure) (bar)	-1
4	Ratio of horizontal to vertical effective soil stresses at soil slip (K)	2.46
5	Initial ring deflection before vacuum is applied, (do)	8%
6	Average wall thickness (mm)	6
7	Mechanical Properties: Hoop Tensile Modulus of Elasticity (GPa)	206.85
8	Moment of inertia (I) of the wall cross section per mm of length of pipe	1.43413E-05

The impact of the pipe deflection on the flexible pipe stability was investigated in this paper by calculating the values of vacuum at collapse, using the above data and conditions.

Definitions and/or formulas of those selected parameters mentioned above are present in the next sections.

Vacuum at Collapse of Buried Pipes, the total horizontal soil pressure on the pipe at spring lines B at soil slip is, (Moser):

$$P_B = K\overline{\sigma_Y} + u_B \tag{4}$$

where P_B is total horizontal pressure on soil at B, K is horizontal effective soil slip stress at B, u_B is hydrostatic pressure in the soil at B, $u_B = (H + D/2)\gamma_w$.

When the horizontal pressure B from Equation (3) is equal to P from Equation (4) the soil is on the verge of slipping instability. For plain pipes, including all of the pertinent variables, the equation of equilibrium of sidefill at soil slip is Collapse Ring Inversion, (Moser):

$$P'(r_r - 1) = K\overline{\sigma_Y} + u_B - (P_A - Ed/m^3)r_r \tag{5}$$

where P' is vacuum at collapse, r_r is $(1+\text{d})^3/(1-\text{d})^3$ equal ratio of vertical to horizontal radii of elliptical pipe, m is r/t, r is mean radius of the circular pipe, t is wall thickness for plain pipe, d is Δ/D is initial ring deflection usually due to backfilling, K is (1+sinφ)/(1-sinφ), at passive resistance, φ is friction angle of the embedment, $\overline{\sigma_Y}$ is vertical effective soil stress at B, u_B is hydrostatic pressure (pore water pressure) at B. If a water table is above the pipe, P_A is soil and water pressure at A, E modulus of elasticity of pipe material, I is moment of inertia of the wall cross section per unit length of pipe, Ed/m^3 equal $96EI/D^3$ where, EI/D^3 (ring stiffness), F/Δ is pipe stiffness equal $53.77\,EI/D^3$.

From Equation (5), the vacuum at ring collapse can be calculated. E/m^3 can be replaced by $96EI/D^3$, or $1.7856F/\Delta$ for other-than-plain pipes.

If the embedment is not cohesionless, as assumed in the above analysis, the same procedure may be used except that the relationship between horizontal and vertical stresses at soil slip must be evaluated for each particular embedment. In the case of ideal cohesive soil, $\overline{\sigma}_Y - \overline{\sigma}_X = 2C$, where C is the cohesion of the soil.

Below a groundwater table, the hydrostatic pressure on the bottom of the pipe is greater than on top. Buoyant pressure on the bottom, y(h+H+D). An empty pipe tends to float, but in this analysis, is assumed to be restrained by the effective soil wedge on top. Collapse occurs from the bottom for large, empty, flexible pipes with a water table above the pipe.

Flexible Pipes in Liquefied Soil Embedment, If the embedment liquefies when a circular pipe is empty, the ring may be subjected to the hydrostatic pressures. If flotation is prevented, catastrophic collapse occurs from the bottom according to the classical equation,

$$\mathrm{Pr}^3/EI = 3; \quad \text{or} \quad \mathrm{h} = (E/4\gamma)(t/r)^3 \qquad \text{for plain pipe.}$$

The performance limit for internal vacuum and/or external soil pressure is ring inversion. Embedment usually prevents total collapse. Critical vacuum, p, is sensitive to radius of curvature. Ring deflection reduces critical vacuum. Because vertical radius of curvature, r_y, is greater than r; ring stiffness, $EI/r_Y{}^3$ is less than EI/r^3, and the vacuum at collapse is less for a deflected ring than for a circular ring.

The stability analysis can include internal vacuum, p, and the resistance of ring stiffness which, for a plain pipe, is EI/m^3. The horizontal stresses on the infinitesimal cube, B, can be equated to passive soil resistance (soil slip). Solving for vacuum, p, at soil slip, for unsaturated soil, (Moser):

$$(P_r - 1) = K\sigma_Y - (P_A - Ed/m^3)r_r \tag{6}$$

For a plain flexible pipe with D/t is 288, and ring deflection = 10%, ingranular embedment with two 0.7m of cover, the critical vacuum is increased significantly by compacting the embedment (increased soil friction angle,). The effect of soil unit weight on critical vacuum is small with soil support with water table above the Pipe:

If the water table is above the top of the pipe, the soil is in no danger of liquefaction if density of the embedment is 90% Standard Proctor (ASTM D698 or AASHTO T-99). The height of water table, *h*, above ground surface, adds to the internal vacuum. The worst case is an empty pipe with the water table above ground surface. Critical vacuum includes water table above the pipe and effective soil pressure. Using the stability analysis of: $(P_r - 1) = K\sigma_Y - (P_A - Ed/m^3)r_r$, but including ring stiffness and vacuum and water table, the equation of stability is, saturated soil, (Moser):

$$(P_r - 1) = K\sigma_Y + u_B - (P_A + \pi r y_W / 2 - Ed/m^3)r_r \tag{7}$$

where *p* is vacuum and/or pressure due to flood level *h* above the pipe, σ_Y is effective vertical soil stress at B, P_A total vertical pressure at A, *K* is (1+sinφ)/(1-sinφ),φ soil friction angle, water pressure at u_B is (h+H+r)y, height of water table above ground surface, y_W is unit weight of water is 9800 N/m^3, *E* is modulus of elasticity of steel = 30(10) psi, *d* is ring deflection (ellipse) $\frac{\Delta Y}{D}$, *D* circular diameter of the pipe, m is r/t equal ring flexibility, *r* is radius of the circular pipe equal *D*/2, *t* is wall thickness, r_r is r_Y / r_X.The term, $\pi r y_W / 2$, is uplift pressure equivalent to buoyancy of the empty pipe. If the pipe is full of water, this term is dropped from Equation (7).

Different deflections have been used in the present paper to investigate the behavior of flexible pipes due vacuum at collapse.

STUDY RESULTS

The values of the selected assessment parameters mentioned above are calculated for flexible pipe of under the selected conditions. The results of the conducted computations for variations in deflection of the investigated pipe versus the critical vacuum are shown in Figure (1).

CONCLUSION AND RECOMMENDATIONS

Limited to the conditions investigated in the present study and based on the obtained results, the following conclusions can be drawn:

(1) Vacuum at collapse, increasing by compacting the soil greatly increases.

(2) Specifications limit ring deflection to 5%. Because it is increasing the maximum vacuum to be larger than atmospheric pressure, therefore the pipe would not collapse. This illustrates the importance of limiting ring deflection if the pipe is to be subjected to vacuum.

(3) If ring stiffness is neglected; i.e. the pipe is so flexible that ring stiffness cannot be depended upon to support any of the soil load. With 8% ring deflection, the

vacuum at collapse is, - 0.55 bar neglecting the ring stiffness term, Ed/rn^3, Ring stiffness does provide resistance to inversion in loose.

(4) For the design of pipes to withstand internal vacuum, a safety factor of 1.5 is recommended. It is prudent to require that embedment soil be denser than critical. Critical density can be evaluated in the soils laboratory. Even without a water table, percolating water and earth tremors tend to shake loose soil do such that ring deflection could increase and reduce internal vacuum at collapse.

(5) Water table reduces the critical vacuum.

(6) The effect of D/t on critical vacuum is minor for values of D/t greater than 240. Soil becomes the primary resistance to vacuum. The pipe is a lining.

(7) The significant variables are ring deflection and soil density.

Based on the above conclusions, caution must be exercised to avoid vacuum at collapse of buried pipes. Also, the importance of limiting ring deflection by soil compaction. The stability of pipelines must receive with the hydraulic analysis in the design phase the same attention as.

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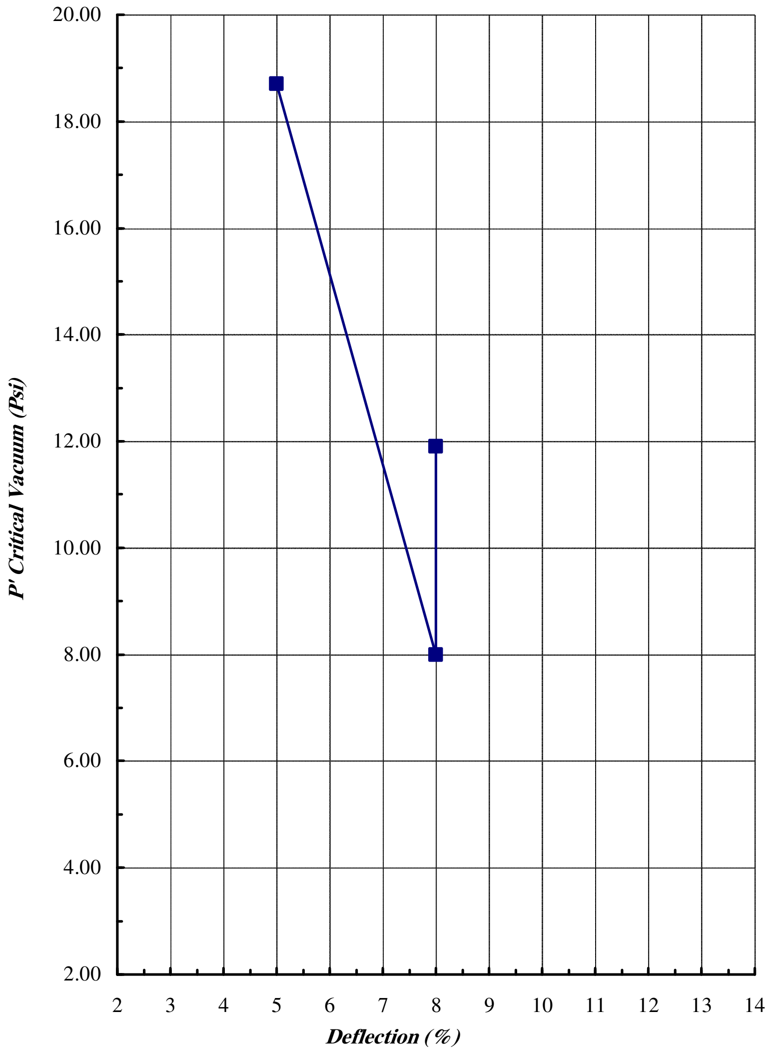

Fig.(1): Deflection vs. Critical Vacuum for pipes