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A model for analysis of the performance of segmented pipelines, crossing a normal fault

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ABSTRACT: A prototype model is proposed for the analysis of segmented buried pipelines, subjected to normal fault movement. A computer programme based on this model has been developed. Series of parametric solutions lead to results and conclusions, regarding the influence of the properties of pipe and soil on the developing stresses and deformations at the critical sections of the pipeline.

1 INTRODUCTION

Strong dependence on lifeline systems is one of the distinctive characteristics of developed urban regions. In the recent years, earthquake safety of lifeline systems, and in particular buried pipelines, has attracted a great deal of attention. As pipeline systems are generally built up over large territories, they are subject to a variety of earthquake induced hazards. Such hazards include: abrupt displacement (as an active fault traverses the pipe), liquefaction, landslides and overstressing due to seismic waves. Resent earthquakes in Greece have demonstrated that buried pipelines are mainly vulnerable to differential soil displacement, such as surface faulting.

Pipelines are usually of two kinds: continuous and segmented. Up today, research was focused on continuous pipes, as many main pipelines are constructed this way. Efficient models for continuous pipelines have been proposed by Wang and Yeh (1985), Vougioukas, Theodossis and Carydis (1991) and Vougioukas and Carydis (1992). Nevertheless, some networks are made of segmented pipes. The performance of such pipes during earthquakes is quite variable depending upon the method of jointing. Rubber gasket joints of both push-on and mechanical pipes have performed best. Lead-caulked joints show some flexibility but vibrational forces of an earthquake will tend to loosen them allowing small leaks to develop later.

The aim of this paper is to compare the behaviour of segmented pipelines that are subjected to permanent ground deformation to the behaviour of continuous pipelines, under the same circumstances. Joints are included in the proposed model, in terms of flexural stiffness; limited rotation is permitted to them but expansion is not permitted.

If future experiments provide data concerning torsional or/and axial stiffness of the joints, these data can be easily included in the model.

2 FORMULATION OF THE PROBLEM

A side view of the model is shown in Figure 1. A long segmented pipeline, that had initially been horizontal, was forced to deform in a vertical plane in order to follow the induced ground deformation. A normal fault is the most probable reason for such a deformation; of course the model can also be used (with some minor alterations) in case of liquefaction or landslide of the soil. The crossing angle β is known, in any case. It is assumed that crossing of pipe and fault (point A) takes place at a node of the pipeline.

Emphasis is given to the vertical movement of the ground for two reasons: first, this is most probable in nature (horizontal movement can only be caused by strike-slip faults); and, second, in case of horizontal movement the problem is simpler, due to symmetry of the two parts of the pipeline. Off course, the procedure that is presented here can be used for horizontal movement, after a few alterations.

Total imposed relative movement between the two parts (ΔV) is divided to two parts (ΔV_1 and ΔV_2). It is called α the ratio $\Delta V_1/\Delta V$. Ratio α is not known a priori.

As soil at the right hand side moves upwards, the relative motion (ΔV_1) of the pipeline is downwards and the reaction to this movement near transition zone (part AB) is due to the bearing capacity

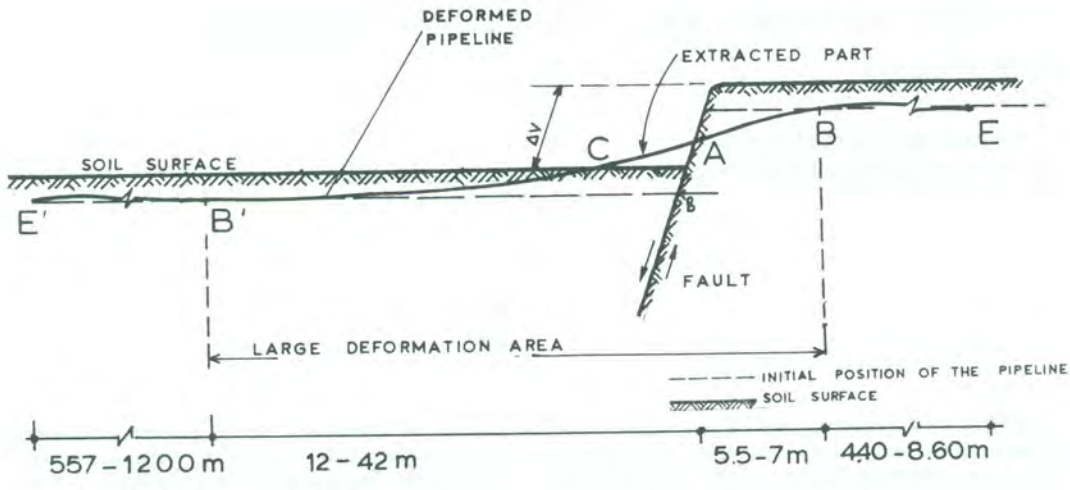

Figure 1. Model of segmented pipeline, subjected to normal fault movement

reaction of soil (P_φ) and it is constant. As soil at the left hand side moves downwards, the relative motion (ΔV_2) of the pipeline is downwards and the reaction to this movement near transition zone (part AB') is due to the uplift reaction of soil (P_u) and it is varying with the depth of the covering soil. Friction forces also exist, that oppose to the sliding F_φ (= n*Pφ) and F_u (= n*P_u).

There exists the possibility that the pipe is partially extracted from covering soil (part AC). In such a case there is no soil reaction at this part.

Parts AB and AB' of the deformed pipe, parts of large deformation, near the transition zone, are considered to be of constant curvature each. Away from the transition zone, and up to where distortion practically ends (parts BE and B'E'), pipeline is considered to consist of two semi-infinite members, neglecting the influence of the joints, as deformations at these areas are very small, anyway. The order of the affected lengths, as determined by the parametric solutions that follow, is shown on Fig.1, to give an impression of their magnitude (not in scale with ΔV). A detail of the transition zone, which interests most, is presented at Figure 2.

As joints are always more flexible than pipe's segments, it is considered that, practically, at part B'CA, angular deformation of the pipe occurs at the nodes only. Same consideration cannot be done for part AB, because it is, in most of the cases, shorter than the length of a single segment; so the pipe behaves as a continuous beam at this part, regardless of the existence of joints. The authors have expounded in detail the equations that govern the upper part in another paper (1992).

As for the lower part, the following equations apply, if the pipe is considered to be inscribed a circle of radius R':

$$R' = \frac{(1-a)\Delta V\{\sin(\theta-\theta_B)+\cos(\theta-\theta_B)\tan\theta_{B'}\}}{1-\cos\alpha'+\sin\alpha'\tan\theta_B}$$

Angle a' is always given a value that permits to an integer number of pipe segments to be extracted from the soil.

Axial force F_C and shear force V_C at point C, are calculated by the formulae:

$$V_c = \frac{A - B*D}{C}, \quad F_c = \frac{B - V_c*\cos(\alpha'-q)}{\sin(\alpha'-q)}$$

where $A = (M_{B'} \times A1) - A2 + A3$

$$A1 = \lambda*\cos(\theta_B + \frac{q}{2})*\tan\frac{q}{2} + (R*\cos\frac{q}{2})^{-1}$$

$$A2 = L*\sum_{k=1}^{N}\sum_{n=N-1}^{0} f_u(k)*\cos(n*q))$$

$$- L*\sum_{k=1}^{N}\sum_{n=N-1}^{0} P_u(k)*\cos(n*q$$

$$A3 = \frac{g(RR - R'\sin(\theta_{B'}))^2}{2R\cos(q/2)} + 2N\tan(q/2)R'\sum_{k=1}^{N} f_u(k)$$

$$RR = \{(R'^2 - (1 - R'\cos(\alpha'))^2\}^{\frac{1}{2}}$$

$$B = L*\sum_{k=1}^{n}\sum_{n=N-1}^{0} f_u(k)\sin(nq) + L*\sum_{k=1}^{n}\sum_{n=N-1}^{0} p_u(k)\cos(nq)$$

$$C = \sin(\alpha'-q) + \tan(q/2) - (\tan(\alpha'-q))^{-1} +$$
$$+\cos(\alpha'-q)/\tan(\alpha'-q)$$

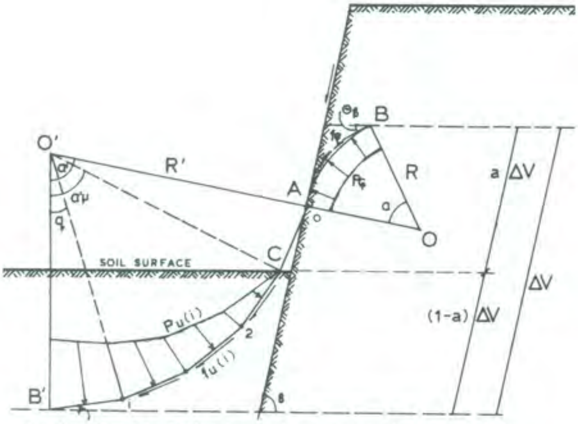

Fig2 Detail of the transition zone of the model

$$D = (1 - \cos(\alpha' - q) / \sin(\alpha' - q)$$

Axial force F_A and shear force V_A at point A, are calculated by the formulae:

$$F_A = F_c - (g * \sin(\alpha' - q) * RR - R' * \sin\theta_{B'})^2) / 2$$

$$V_A = V_c - (g * \sin(\alpha' - q) * RR - R' * \sin\theta_{B'})^2) / 2$$

Adjacent pipe segments at point B' form a relative joint rotation $\theta_{B'}$, which is calculated to be:

$$\theta_{B'} = (K_{rot} * q / 2) / (2\lambda EI - K_{rot})$$

As it is described below, at the 'iterative procedure' chapter, compatibility of 'permissible' (due to stresses) and 'geometric' (due to geometry of deformations), should be equal.

Geometric elongation is calculated to be:

$$\Delta_G = R * a - (R * \sin\alpha - a * \Delta V * \cos(B - \theta_B) / \cos\theta_B$$

for the upper part, while, for the lower part:

$$\Delta_{G'} = L * N - (R' \sin\alpha - (1 - a) * \Delta V * \cos(B - \theta_B)) / \cos\theta_B$$

Permissible elongation is calculated to be:

$$\Delta_P = (A_p R / EI) * \big(F_T * \sin\alpha +$$

$$+ (V_T + f_\varphi * R)(\cos\alpha - 1) + p_\varphi * R * (\alpha - \sin\alpha)\big)$$

for the upper part, while, for the lower part:

$$\Delta_{P'} = (N * A * L * \sigma_1 * (1 / E_1 - 1 / E_2)) +$$

$$+ (1 / A_p * E_2) * \sum_{M=1}^{NA} (F_j(M) * L) - 0.5 * F_u(M) * L^2)$$

It may be mentioned here that, though these equations are extracted for fault movement causing tension to pipeline, they could also be used for the case of fault causing compression, provided that no buckling phenomena take place. In such a case, soil pressure has to be induced with negative values to the above equations. Soil movement causing tension produces always more severe deformation, because 'geometric' elongation is always larger in such a case.

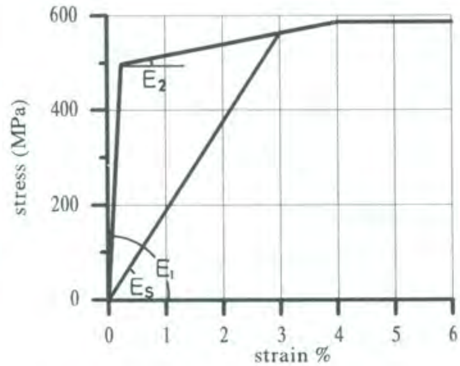

Fig.3 Stress-strain curve for X-70

3 MATERIAL PROPERTIES

The properties of steel X-70, that is widely preferred for the construction of pipes, is used in this study. Stress-strain curve for X-70 is presented in Figure 3.

It is approximated by a trilinear curve, having the initial elastic portion up to the first yield point σ_1, then a second linear part having a much smaller slope σ_2, up to the constant ultimate yield strength The first linear portion is considered as the elastic region and the second linear portion is considered as the inelastic region. The slope of the first linear portion is denoted as E_1 and the slope for the second linear portion as E2.

If the material exceeds the first yield point, then the secant modulus of elasticity (Es) denotes the ductility demand of the pipe.

As for the joints, it has been considered that they have the properties of quite flexible linear elastic rotational springs (their stiffness not exceeding 50% of the pipe's flexural stiffness). It has also been considered that, due to their small length, they are very rigid axially. Provision is taken so that any other properties of elastic (linear or not) springs can be used to resemble the joints, in terms of rotation and/or displacement.

4 SOIL CHARACTERISTICS

The pipe is buried in a trench and backfilled with sand. The properties of the sand are considered as:

$\gamma = 17.6$ KN/m3

$\varphi = 35.0$ deg

$\varphi_p = 20.0$ deg

For the upper part, values proposed by Loizos (1977) are used for the estimation of the bearing capacity (P_φ)of the soil. As large deformations are examined, P_φ is constant for part AB. It is assumed that the trench is deep enough, so that the properties of the sand govern; in case of very

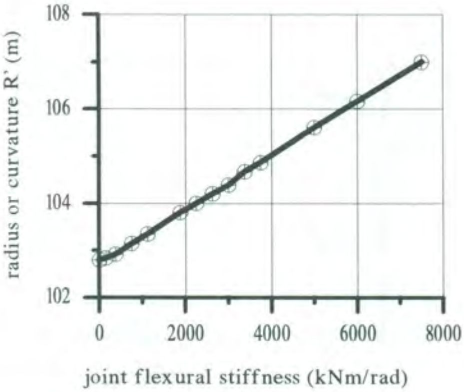

Fig.4 Effect of joints' stiffness on radius or curvature of the lower part

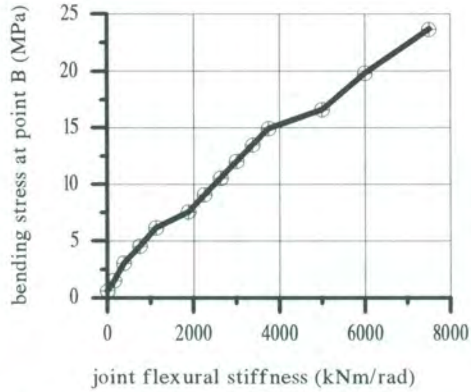

Fig.7 Effect of joints' stiffness on the bending stress at point B

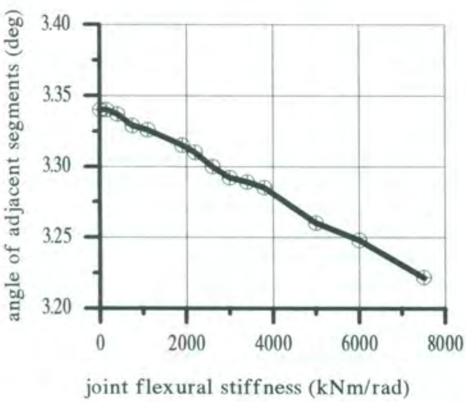

Fig.5 Effect of joints' stiffness on the angle formed by adjacent segments

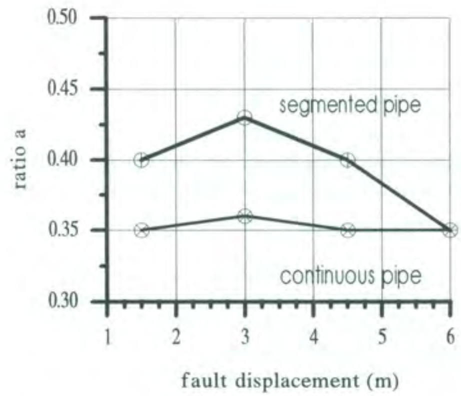

Fig.8 Effect of fault displacement at the ratio a

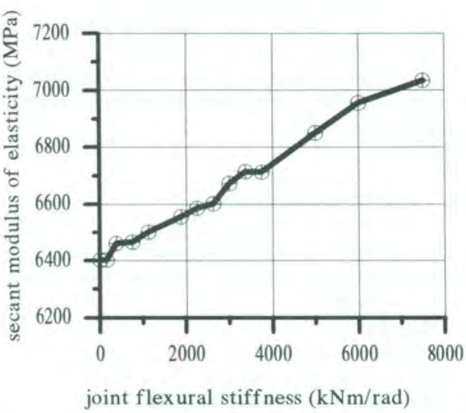

Fig.6 Effect of joints' stiffness on the secant modulus of elasticity ofsteel at the lower part

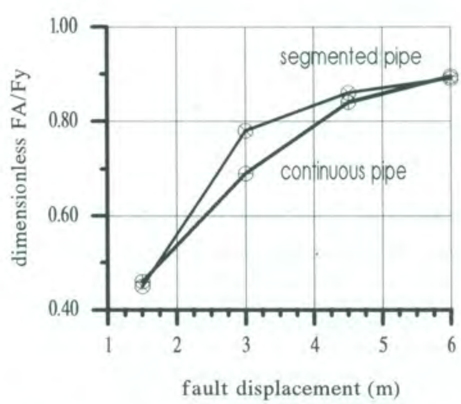

Fig.9 Effect of fault displacement at the normalized axial force at point A (F_A/F_y)

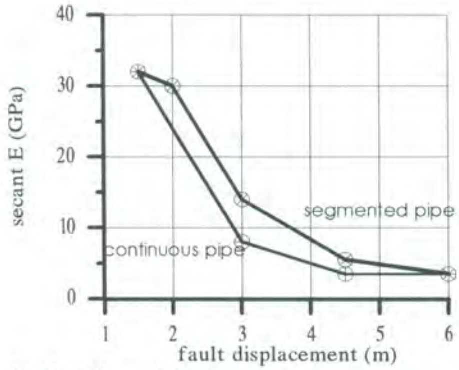

Fig.10 Effect of fault displacement to the secant E at point B'.

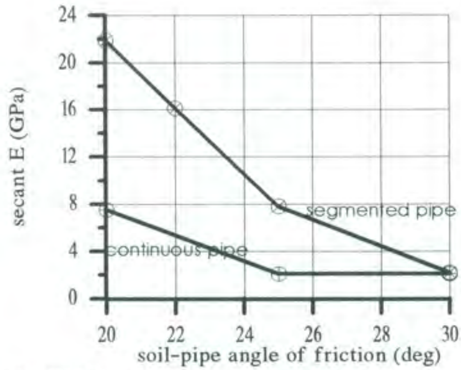

Fig.11 Effect of soil-pipe angle of friction to the secant E at point b'.

shallow trench, the properties of the surrounding soil should be induced

For the lower part, values proposed by Trautmann, O' Rourke and Kulhawy (1985) are used for the estimation of the reaction of the soil to the pipe uplift (passive pressure). This reaction is analog to the depth of soil covering the pipe at each point, so it is reduced as the pipe tends to be extracted from the soil

Away from the transition zone, values proposed by Spangler and Handy are used for the estimation of soil reaction to the pipe movement; these values differ for either part of the pipe.

Friction is analog to the pressure at every point of the pipeline.

5 ITERATIVE PROCEDURE

An iterative procedure, with three series of iterations is introduced to determine the fault movement resisting capacity for the pipeline. This procedure has to be used because the number of the equations is less by two than the number of the unknowns. The steps of the procedure are as follows:

1. The parameters under consideration are (in parentheses the initial values): the pipe-soil angle of friction (20 deg), the material properties of the pipe (X-70), the relative movement ΔV(4.5m), and the angle β between fault and pipe.(70 deg) .Other data are the Diameter of the pipe (1070 mm), its thickness (14.3 mm), the length of the pipe segments (6m) and the depth of cover (1.435 m)

2 ΔV is divided in two parts, ΔV_1 and ΔV_2. It is called a the ratio $(\Delta V_1/\Delta V)$.

3 For the upper part of the pipe: Angles α and θ_B, are given initial values. An secant modulus of elasticity is estimated for the pipeline's material. The soil reactions and the corresponding friction forces, the radii of curvature, the resulting forces and the geometric deformation ΔG of pipe are calculated.

4 The permissible deformation ΔP of the pipe is calculated in this step, using the stress-strain relations at every part of the model.

5 Compatibility demand requires that the geometric (ΔG) and the permissible (ΔP) deformations of each part of the pipe are equal.. If this is not achieved, α and θ_β are given new values and steps 1- 3 are repeated

6 The secant modulus of elasticity of steel is calculated, resulting from calculated stresses and strains.

7 The initial value of the secant modulus of elasticity of steel is compared to the calculated value and if this is not achieved, the iteration procedure 2-6 is repeated until the procedure converges.

8 The resulting forces and displacements for the upper part of the pipe are calculated in this step.

9-14 Steps 3-8 repeated for the lower part of the pipe.

15 Balance of resulting forces at section A is required. If this is not verified, a is given a new value and steps 3 -15 are repeated.

16 As the iterative procedure converges the 'final solution' is reached and the results are printed.

6 RESULTS AND CONCLUSIONS

First, it has been examined if the properties of the joints affect considerably the behaviour of pipelines, when they are subjected to abrupt relative displacement. Figures 4-6 show that influence of joints is negligible on the curvature of the large deformation area, on the flexibility demands of joints (in terms of required deformation angle between adjacent segments) and of the ductility demands of the pipe (in terms of secant modulus of elasticity). Figure 7 shows, however, that the more stiff the joints are, the more bending stress is induced to them.

Comparison between segmented and continuous pipeline has also taken place. Figure 8 proves that the geometry of the problem is affected enough, while figures 9 and 10 indicate that performance of segmented pipelines is better, if compare to continuous ones (less axial force and reduced ductility demand, under the same circumstances.) Figure 10 proves that elimination of friction between soil and pipe tends to better behaviour of pipelines; as it is shown, this is of greater importance in the case of segmented pipelines. The length of the pipe segments and the pipe diameter do not mainly affect the response of the pipe.

Default values of parameters are as follows:

- Rigidity of joints: 1500 kNm/rad
- Length of the pipe segments: 6 m
- Fault displacement: 4.5 m
- Crossing angle: 70 deg
- Friction angle between pipe and soil: 20 deg
- Pipe diameter: 1070 mm
- Pipe thickness: 14.3 mm
- Depth to the upper edge of the pipe: 1.435 m

Despite the efficiency of the proposed model, the results are indicative of the pipelines' performance, as local inhomogeneity is not taken into account. In the field, local conditions might not permit the pipe to deform the way considered; this could change the output results quantitatively.

It has to be mentioned that the described model does not include any failure criteria, that means that it has to be examined if output results (in terms of deformation, tension or required ductility) are compatible with the safe performance of the pipe.

Taking into account the two previous paragraphs, the following values of the examined parameters are suggested as limits for the aseismic design of underground pipelines:

- crossing angle greater than 65 deg
- friction angle pipe/soil less than 20 deg
- pipe thickness greater than 12.5 mm
- pipe depth less than 1.4 m
- pipe diameter less than 1400 mm

Final conclusion is that the more permission of relative deformation is given to buried pipelines, the safer performance is expected

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