ASSESSMENT OF THE VULNERABILITY OF JOINTED D.I.P. CROSSING ACTIVE FAULTS

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A numerical assessment of the vulnerability of underground jointed ductile iron pipelines (D.I.P.) subjected to fault displacements is performed. An outline of the capabilities of the in-house specialized program used in the analyses is given. The major parameters affecting pipeline behaviour, namely pipe diameter, fault crossing location and fault crossing angle have been studied and vulnerability charts produced. In addition, the possibility of failure at multiple locations, and patterns of multiple failures are identified. The results of this research provide useful guidance to locating failed pipes after an earthquake, and defining the magnitude and scope of failure at a particular location.

Key words: *Jointed D.I.P., Failure analysis*

1. INTRODUCTION

A number of particularly destructive earthquakes hit the world in recent years, e.g. the 1995 Kobe earthquake, the 1999 Chi-Chi and Kocaeli earthquakes. Along with the usual heavy damage to building structures, these earthquakes exposed the seismic vulnerability of utility pipelines. The reasons for this can be put into two categories; first, the fact that the earthquakes struck urban areas with well developed underground infrastructure and second, the still insufficient understanding of the behaviour of underground pipelines and the process of their failure, resulting in inadequate design codes or lack of such codes in the first place. Field surveys of damages pipelines have repeatedly confirmed that a large proportion of the failures are due to joint failures that lead to discontinuities in the pipeline body. Such joint detachments are often accompanied by large deflections inducing material and geometrical nonlinearity effects in the pipe behaviour. The damage is particularly severe when pipes cross fault dislocations.

In order to reliably evaluate the overall pipeline behaviour, a comprehensive numerical method for limit state simulation of buried pipelines was developed to facilitate the drafting of new codes for design of such pipelines.

The analysis of the behavior of buried pipelines has been done by many methods in the past.

Many closed form solutions to the pipe–soil interaction problem based on beam on elastic foundation have been proposed by Kennedy[1)], and Wang[2)]. Such methods are excellent for grasping the nature of the problem but cannot be applied when large deflections or material nonlinearities are present.

The Finite Element Method (FEM) has been routinely applied for pipe analysis; numerous examples of beam, shell or combined models can be found in the literature[3)]. Transfer matrix methods have also been developed[4)]. While the FEM analyses are successful in revealing most of the features of pipeline behaviour, rupture and detachment at joints cannot be dealt with; for the shell version the computation effort is too great to allow large models consisting of many pipe segments to be analysed. The main purpose of the proposed method is to extend the domain of pipeline analysis through the failure and post-failure stages, while taking advantage of the efficacy of simple elements in the modelling.

2. MODELLING AND SOLUTION METHOD

(1) Modelling of the pipe body

The model consists of lumped masses (elements) connected by sets of springs as shown in Figure 1. Each spring set consists of an axial, bending and torsional components derived from beam theory.

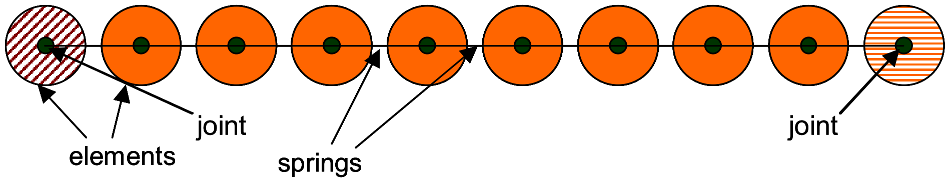


Figure 1. Model of a pipe

Figure 2 shows the forces and displacements at the ends of a 3-D beam segment with Young's modulus *E*, second moment of area *I* and length *L* which are linked by these springs. A plane projection is shown for simplicity.

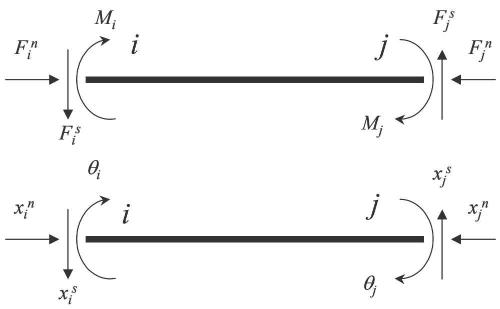


Figure 2. Forces and displacements at the ends of a beam segment

(2) Solution procedure
The solution is based on the double integration of the Newton equations of motion for each element. The motion of an element is considered uncoupled from the motion of the rest during a single time step, thus eliminating the need to assemble a stiffness matrix. Coupling, which of course exists, is accounted for by updating the spring forces at every time step. An element then moves due to the out-of-balance force appearing on summation of the forces in all springs originating from it. For the system to reach equilibrium two types of damping are applied. First, the relative motion between elements is damped by a coefficient of damping calculated from the critical damping ratio of the material of the structure (steel, plastic, etc.). This is termed local damping. In addition a small amount of viscous damping works on the absolute velocities of the objects. This is referred to as global damping and represents the resistance of the medium in which the structure stands (soil). The method is inherently dynamic, geometrically non-linear, and can accommodate easily arbitrary amounts of rigid body motion.

(3) Modelling of soil-pipe interaction
The soil surrounding the pipeline is modelled by pairs of springs having axial stiffness only, with one end attached to a lumped mass and the other end fixed. One spring is perpendicular to the pipe representing the direct contact between pipe and soil, and the other tangential to it representing the drag between pipe and soil. Input displacements are specified at the fixed ends to simulate fault displacements. The direct soil springs are active only in compression, whereas the drag springs are active in both directions of relative displacement between pipe and soil. The direction of all soil springs is modified at each time step to preserve the angle they made with the pipe in the initial undeformed configuration.

(4) Modelling of joints
A joint is introduced to the pipe model in the following way. Two elements instead of one are specified at nodes where joints are present, e.g. the elements with lighter colour in Figure 1 have been added since there are joints at these locations. The force and moment contributions due to presence of a joint are computed according to the mechanical behaviour of the joint, and added to the total driving force and moment acting on the joint elements. Force contributions are computed according to the axial behaviour of the joint, and moment contributions according to it's bending behaviour. The relative rotation of the joint elements needed for computing the moment contributions is obtained directly as the difference of the absolute rotation angles of the two elements.

For obtaining the relative expansion or contraction, an assumption needs to be made for the axial direction of joint displacement. This has been

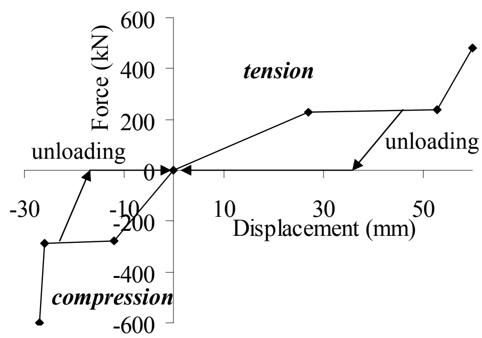


Figure 3. Constitutive behaviour of a typical joint

assumed to be the axis of one of the adjoining pipe segments, which is called the *reference beam*. It has been further assumed that a relative displacement between the joint nodes in the lateral direction does not occur. The axial behaviour of an anti-seismic mechanical joint (ASMJ) obtained by standard experiment[5)] is shown in Figure 3. It is a good example of the complexity of behaviour of a mechanical joint. The features important to the incorporation of such a constitutive behaviour into a computer program are as follows:

1. The behaviour in the direction of pipe axis (tension/compression) as well as in bending is characterised by several distinct stages, each stage corresponding to a particular mechanical event taking place inside the joint. The program algorithm is so designed as to allow the treatment of a sequence of as many linear stages as necessary to fully describe the joint behaviour in a particular. This approach provides generality of treatment at no added computational cost. Notably curved stages can always be interpolated in a piecewise linear manner.

2. Since the mechanical events in the tension and compression regimes are entirely different the load displacement curves for tension and compression are also different. To this end the program algorithm allows for separate treatment of tension and compression.

3. Experimental data is normally available for continuous loading only, so unloading curves as well as points of transition between tension and compression or clockwise bending and counter-clockwise bending will not be known so reliable input data cannot generally be available for these items. The situation is further complicated by the unavailability of data for the interaction between the axial and bending behaviour of joints. In the program algorithm the axial and bending behaviour are considered independent, and gradients for unloading are specified for each stage. The transition between loading direction is set at the zero point, and reloading does not occur before the distance/angle between the joint elements reaches the amount of previously accumulated plastic flow displacement/angle.

4. One or more stages of the constitutive behaviour paths may have large gradients of loading or unloading. These stages correspond to situations where the two pipe segments meeting at the joint come in direct contact or in contact via a stiff joint part, i.e. become interlocked. In fact, since an experiment on a joint alone is practically impossible, such stages may be thought to correspond to deformations in the adjoining pipe segments used in the experiment. Given the time-stepping nature of the algorithm, that would necessitate a decrease of the time step needed for stable computation. This is computationally inefficient, so a special handling technique was developed for these stages. The displacement or rotation of one of the joint nodes is constrained to this of the other node until the maximum or minimum force or moment for the stage is reached. The values for comparison to the ultimate values of the stage are taken from the *reference beam* of the joint. Such stages are termed *locked*.

(5) Plastic hinges in the pipe body

Apart from the joints, failure may occur due to excessive deformations within the pipe body. The handling of plastic deformations and failure due to the axial forces in the pipe has been explained in *Solution procedure* above. The formation of plastic hinges in the pipe body is handled by introducing joints within a pipe segment. For these joints, only one stage is specified for the constitutive behaviour in the axial direction (tension and compression), and is set to *locked*. The bending behaviour is made-up of three stages; the first is locked, the second is the transition between the yield bending moment M_y and the ultimate bending moment M_u of the section, occurring over joint rotation angle θ, and the last has a decaying gradient that represents the gradual failure of the cross section at the location of plastic hinge formation. Interaction between bending moment and axial force is presently not considered.

3. CASE STUDIES

(1) Analysis setting

A pipeline crossing a strike-slip fault was analysed to test the integrity of the developed program. The geometry of the model, as well as the properties of the pipe and the soil springs[6)] are shown in Figure 4. Three commonly used ductile iron pipes with E=1.57x10^{8}kN/m^2 and yield stress σ_y=1.95x10^{5}kN/m^2 are considered. Their properties are shown in Table 1. The model consists of five 5m pipe segments interconnected by four ASMJ, with constitutive behaviour as shown in Figure 5. The plastic hinge parameters M_y, M_u, and θ are shown in Table 1. Plastification due to axial forces is also considered. A fault displacement of 2m over time of 2sec. is applied to the model by moving the ends of soil springs enclosed in dashed boxes in Figure 4. Five crossing points were investigated; one at joint 2, and additional four at distances 1m, 2m, 3m, and 4m to the right of joint 2; the distance between joint 2 and the crossing point is designated by *l*. The crossing angle α is varied between 30° and 120° at 30° increments for each crossing point.

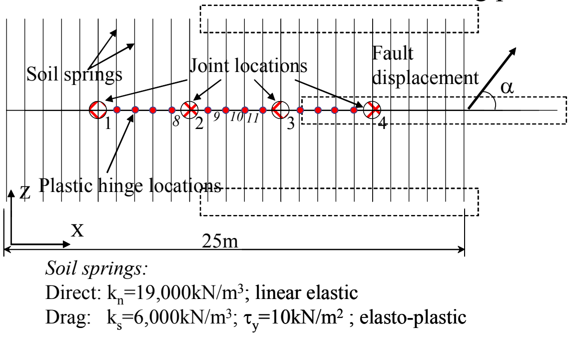
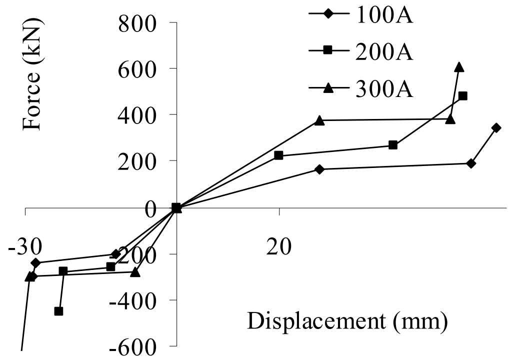
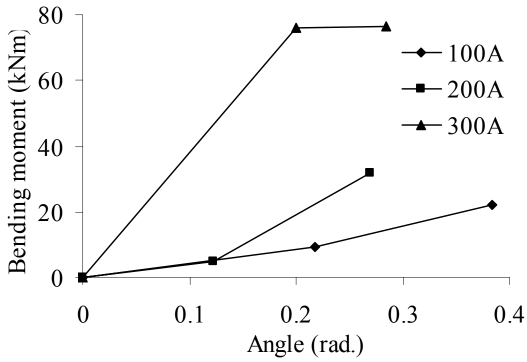


Figure 4. Analysis model



(a) Axial behaviour



(b) Bending behaviour

Figure 5. Constitutive behaviour used in analyses

Table 1 Pipe properties

	100A	200A	300A
A (m²)	2.92x10⁻³	5.65x10⁻³	8.39x10⁻³
I (m⁴)	4.42x10⁻⁶	3.16x10⁻⁵	1.04x10⁻⁴
M_y (kNm)	13.7	55.1	125
M_u(kNm)	16.7	67.3	152
θ (rad) 3)	0.6	0.45	0.3

(2) Results and discussion

The joint failure log for pipe 100A is shown in Table 2. Characteristic deformed shapes for the same pipe are shown in Table 3, where values of fs closest to failure were taken from the program output.

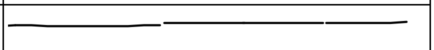
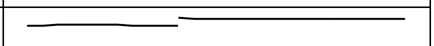
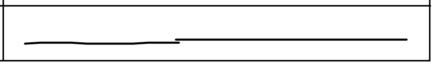
Table 2 Failure log for pipe 100A

l (m)	α (deg)	failure sequence			
		first		second	
		fs (m)	fm	fs (m)	fm
0	30	0.31	2t		
	60	0.48	2t		
	90	1.13	1t	1.19	8b
	120	0.12	2c		
1	30	0.31	4t		
	60	0.46	2t	1.10	9b
	90	0.60	2b	0.72	9b
	120	0.12	2c	0.72	9b
2	30	0.30	4t		
	60	0.46	3t	1.12	9b
	90	0.93	3t	0.95	9b
	120	0.12	2c	0.77	10b
3	30	0.30	4t		
	60	0.45	3t	1.10	10b
	90	0.91	3t	0.93	10b
	120	0.12	3c	0.71	11b
4	30	0.30	4t		
	60	0.45	3t	1.10	11b
	90	0.92	3t	0.94	11b
	120	0.12	3c	0.73	12b

The joint failure modes shown in Table 2 agree well with the direction of fault displacement, i.e. failure in tension occurs under predominantly tensile loading, failure in bending under predominantly bending loading, and failure in compression under predominantly compressive loading. In the table, fm stands for failure mode, fs for fault slip, t, c, and b for tension, compression and bending respectively. The number in front of a failure mode is the number of the joint that failed in this mode.

In all analyses for α = 30° it is seen from the table that all joints fail almost simultaneously and the mode of first failure is tension. At the moment just before failure the axial forces in the pipe under the above loading are uniformly distributed, which means that any joint is in danger of failing. The failure of the first joint results in a large momentary imbalance of forces, which in some analyses brings about the failure of the rest of the joints. It is

Table 3 Deformed shapes (100A)

l (m)	α (deg)	fs (m)	Shapes
0	30	0.4	
	60	0.5	
	90	1.0	
	120	0.3	

believed that in reality this type of sudden progressive failure is not likely to occur, and is not shown in the above table. The reason it occurs during the simulation is that the joints are assumed to fail in a brittle fashion in both tension and compression. The actual softening branch of the joint behaviour just before failure is not known, but it seems appropriate to apply some kind of softening rule in order to avoid such failure mechanism during analysis. The same phenomenon is observed for $\alpha = 60°$ and $\alpha = 120°$ although for these crossing angles not all joint fail simultaneously.

In general, the joint that fails first in tension is the one nearest to the fault crossing point, i.e. joint 2 or joint 3. However there are exceptions to this rule, e.g. the cases with l = 3m and l= 4m, $\alpha = 30°$ where joint 4 fails first.

Interestingly, the first joint to fail for $\alpha = 90°$ is more likely to be in tension rather than in bending, regardless of the absence of direct tensile component of the input motion relative to the undeformed pipeline. This can be attributed to a second-order geometrical effect (the stretching of pipe due to transversal loading).

Another interesting finding is that the tensile and compressive failure of the joints is not very sensitive to the crossing point location and depend solely on the crossing angle. The case for $\alpha = 90°$ is an exception to this rule.

The results in Table 2 also provide information about the failure process that certain configurations may undergo under progressive loading. A typical scenario of progressive failure is one of a joint failing in tension followed by a bending failure in the pipe body (numbers larger than 4 in the failure log). The failure of a joint in tension in principle precludes further tensile joint failure because the continuity, and hence the ability of the pipe to transfer axial force is severed. On the other hand, the increasing flexural deformations due to the transversal component of fault slip may cause damage to the pipe body.

For pipes 200A and 300A under crossing angle 90°, failure only in the pipe body was observed for l=2m and l=3m.

Finally, if we have to classify the damaging potential of the three loading regimes, the most dangerous is the compressive one, followed by the tensile one, and last the bending one. The quantitative expression of the damaging potential in terms of fault slip at failure is given in Figures 6, 7 and 8 for pipes 100A, 200A and 300A respectively. These figures represent the fragility curves for the individual pipes and can be used directly for design or failure assessment. If we plot together the fragility curves of all pipes for a particular crossing location as in Figure 9, we see that the smaller diameter pipes perform slightly better. This is probably because larger plastic hinge rotation angle was assumed for these pipes, based on the study of Takada et al [3]. This assumption needs further study by detailed FE shell modelling of the formation of plastic hinges in the D.I.P..

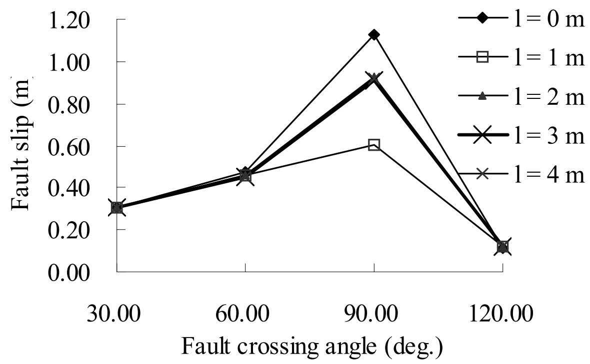


Figure 6. Fragility curves for pipe 100A

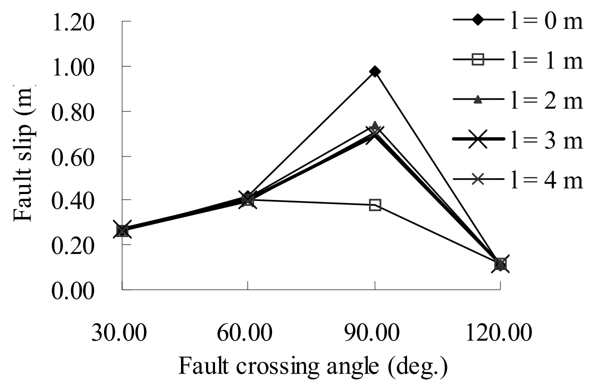


Figure 7. Fragility curves for pipe 200A

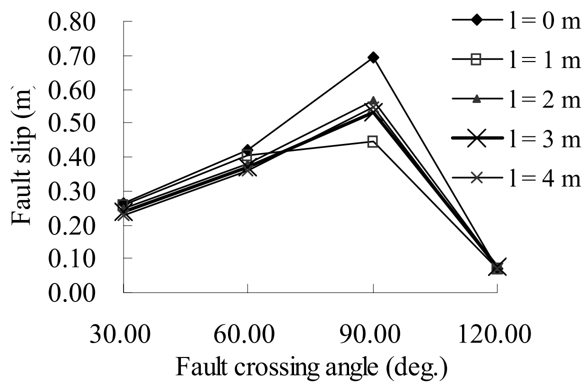


Figure 8. Fragility curves for pipe 300A

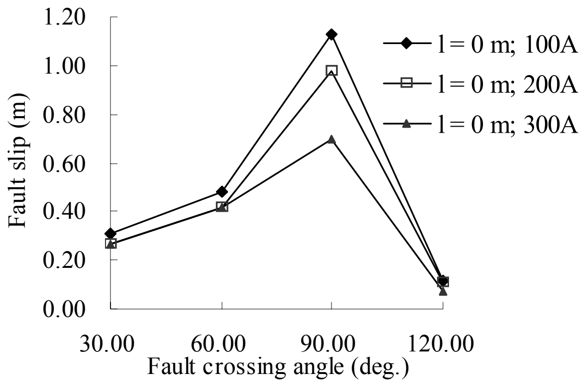


Figure 9. Fragility curves comparison

4. CONCLUSIONS

A comprehensive numerical method for limit state simulation of buried jointed pipelines is presented.

The method is capable of tracing the behaviour of pipelines until and after failure of the pipe body and detachment at joints, thus allowing the physical damage to a pipe network to be better estimated. The solution algorithm is based on the direct integration of the uncoupled equations of motion of the elements. The implementation of such solution algorithm ensures that the behaviour of a pipeline can be investigated for any magnitude of ground displacements.

In order to minimize the computation time the pipe body is modelled by line elements. The basic mechanical properties of all common pipe joints e.g. stiffening in compression, detachment in tension, fracture in bending can be considered.

Fragility curves were derived for the joint failure of a pipeline of common diameters crossed by a fault at different locations and angles.

The failure mode of the joints is commensurate with the loading regime except for the case of pure transversal loading and crossing point exactly at a joint, where the first failure is in tension instead of bending.

The pipeline is found to be most in danger under compressive and tensile loading regimes, and capable of withstanding fault displacements of about 1m under purely transversal loading.

The joints likely to break are those adjacent to the pipe segment crossed by the fault. If multiple failure occurs, one failure is at a joint and another in the pipe body in this sequence.

The fault displacement at failure is found to be insensitive to the crossing location for the tensile and compressive regimes. This indicates that the performance of the pipeline cannot be improved by varying the crossing location, and joints with larger axial deformation allowances are needed to make the performance of the pipeline in the axial direction commensurate with its performance in bending. Alternatively, layouts with more closely spaced standard joints need to be studied further. Also, further analyses for crossing angles between 60° an 120° need to be done in order to define better the range of sensitivity of joint performance to the crossing angle.

Although the first failure in most of the studied cases occurred at a joint, it was found that for crossing angle 90° the fault slip at failure is related to the rotation capacity of the plastic hinges specified for a particular pipe diameter. Larger rotation capacity resulted in large failure slip. Further study is needed to find out the mechanism by which the performance of the pipe body influences the performance of the joints.

The results obtained in this study can be used as a design guidance for small to medium diameter jointed gas pipelines crossing active faults.

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