Engineering Analysis of an Offshore Pipeline on an Escarpment in a Seismically Active Zone A Case Study in the Caspian

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SUMMARY:
A large number of offshore developments are being considered and are in progress in seismically active regions. A development in the seismically active Caspian Sea region, features installing several subsea water injection lines from an existing jacket to a remote manifold several kilometres away, the primary intent being to enhance the existing production. The water depth at the jacket is approx 160m with a gently sloping seabed and an escarpment which is encountered 400m away. The pipeline is laid over the escarpment and connects to a manifold 4km away where the water depth is 280m. The concern is about the integrity of the water injection lines and facilities in the event of a seismic event. The intention of this paper is to assess the engineering requirements to protect the jacket from the generated loads from the pipeline due to a major seismic event.

Keywords: pipeline, escarpment, soil, seismic, anchor

1.0 INTRODUCTION

The client, BP, proposes installing a subsea water injection system to boost the current production rate from the East Azeri (EA) jacket. The subsea water injection transport system to the manifold location consists of a 12” (nominal bore) riser descending down the side of the jacket. The riser terminates in a manifold to which two 8” flexible flow lines are connected. The two 8” flexible flow lines tie-in to a water injection manifold approximately 4km away.

At the jacket the water depth is approx 160m with a gently sloping seabed; an escarpment is encountered 400m away to a water depth of 280m close to the manifold. *The entire area is seismically active and hence the concern about the integrity of the water injection lines in the event of a seismic event.*

The current philosophy is to protect the jacket j-tube from the generated loads from the pipeline due to seismic events. Hence, an anchor for the flexible lines may be required at a point away from the jacket. In the event of an earthquake, the anchor will protect the more valuable assets. The type of anchor will depend on the magnitude of the load and would be one of the following: suction, drag, or driven piles.

An FE analyses using PLAXIS was carried out to estimate the down-slope deformations due to a strong earthquake (a 3,000 year event). The results of the FE analyses were used to carry out the engineering assessment of the pipeline anchor loads at the jacket-end. The main objective of these analyses was to estimate the maximum reaction at the anchor location.

2.0 SEABED PROFILE

There were several routes from the jacket to the manifold. The survey data for the seabed was carried out by an offshore surveying company appointed by BP. Norwegian Geotechnical Institute (NGI) undertook the assessment of the 3,000 year return period earthquake to assess the movement and slope stability of the route. The seabed profile is shown in Fig. 1.

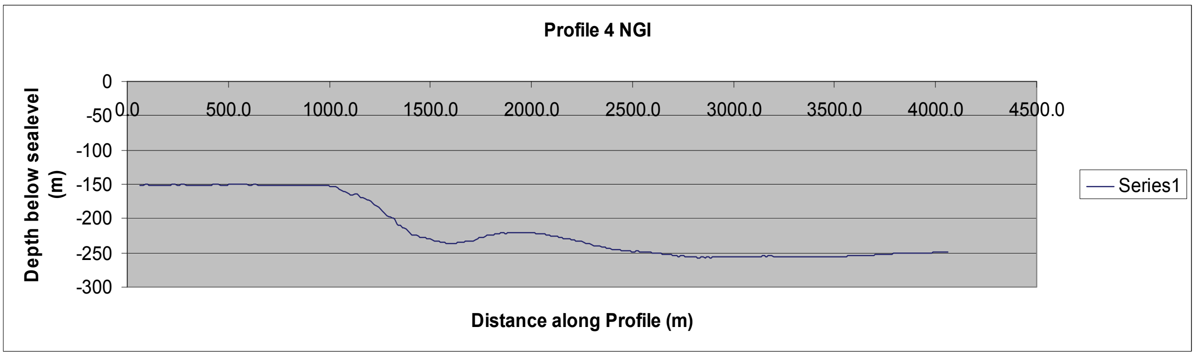

Figure 1. Seabed Profile

The escarpment referred to above is approximately 400m from the EA Jacket. Seismic induced deformations of the soil have been shown to be the highest in the region of the escarpment.

The purpose of the present analysis is to compute the time histories of the earthquake-induced displacements at a number of points along the slope. These time histories will be used to assess the anchor loads.

2.1 Description of NGI 2-D FE model

The problem was simulated by NGI in plane strain conditions using the PLAXIS 2-D finite element code (PLAXIS, 2007). The PLAXIS, 2007 model was used for the seismic response analysis of the soil block.

In order to avoid disturbances due to possible reflections, the boundaries of the FE model should be taken sufficiently far away from the region of interest. Therefore the dimension of the FE model is taken equal to 2800m long and 300m high on the left side and 200m on the right side. The slope is 85m deep and has a horizontal length of 590m.

The finite element mesh of the PLAXIS model was composed of 860 fifteen-node triangular elements. A finer mesh discretisation was used for the region of interest around the slope. This is illustrated in Fig. 2.

The displacement boundary conditions of the mesh consist of the standard PLAXIS boundary condition; i.e. horizontal restraint at the two sides of the mesh and fully restrained at the bottom of the mesh.

The model was also equipped with absorbent boundaries on the two vertical sides and the earthquake accelerations were specified along the bottom boundary. The purpose of these special boundary conditions was to avoid the spurious reflections of the waves on the model boundaries. The default setting for standard absorbent boundaries in PLAXIS was used for earthquake analysis.

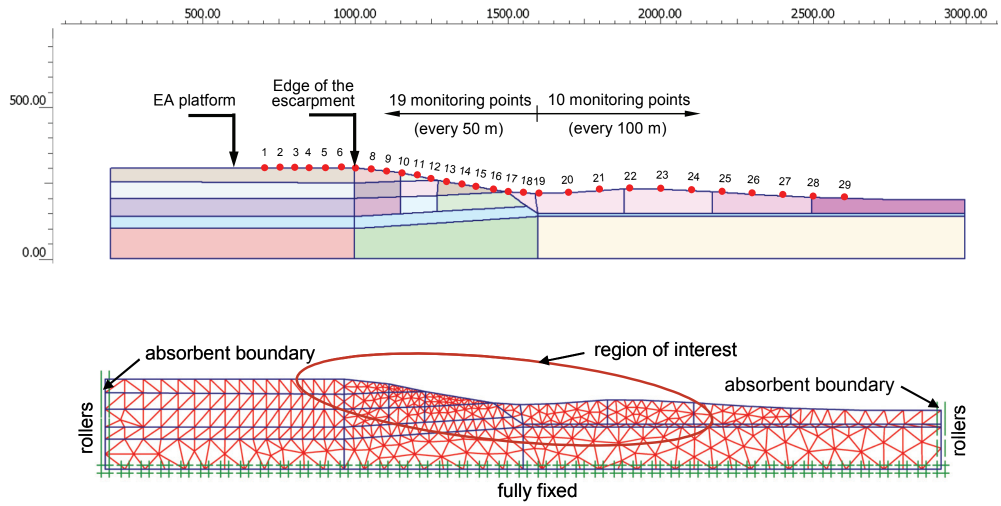

Figure 2. Location of points for monitoring earthquake-induced motion (NGI Model)

2.2 Soil data used in NGI model

Soil boring data were obtained for several points along the route and were conducted by soil investigation consultant Fugro. The stratification given in these profiles was used by NGI to establish the mechanical properties of different soil strata from the interpretation of field and laboratory soil data.

Based on interpretation, of Fugro supplied data by NGI, the undrained shear strength was estimated to be $4kN/m^2$. Hence, for the calculation of soil springs, a mud-line undrained shear strength of $4kN/m^2$ was used for soil spring stiffness calculations.

2.3 Seismic loads

For the earthquake analysis the PLAXIS model was excited separately in the horizontal and vertical directions at the base, which was considered as rigid. Fig. 3 presents the horizontal and vertical earthquake time histories.

Time history records in the Caspian Sea region were not available so useable data had to be generated. Establishing probable magnitude for a future earthquake is usually carried out by seismologists. Consultants EQE first established the likely magnitude of the earthquake for the 3,000 year event. Having established the magnitude, suitable time history records were researched from the California region. These records correspond to the horizontal (component 360^0) and vertical components of the earthquake records registered at station New Hall, LA County Fire Station during the Northridge earthquake of 1994 and normalised to represent an event with a 3000 year return period. The details are available in the report prepared by EQE in 1996.

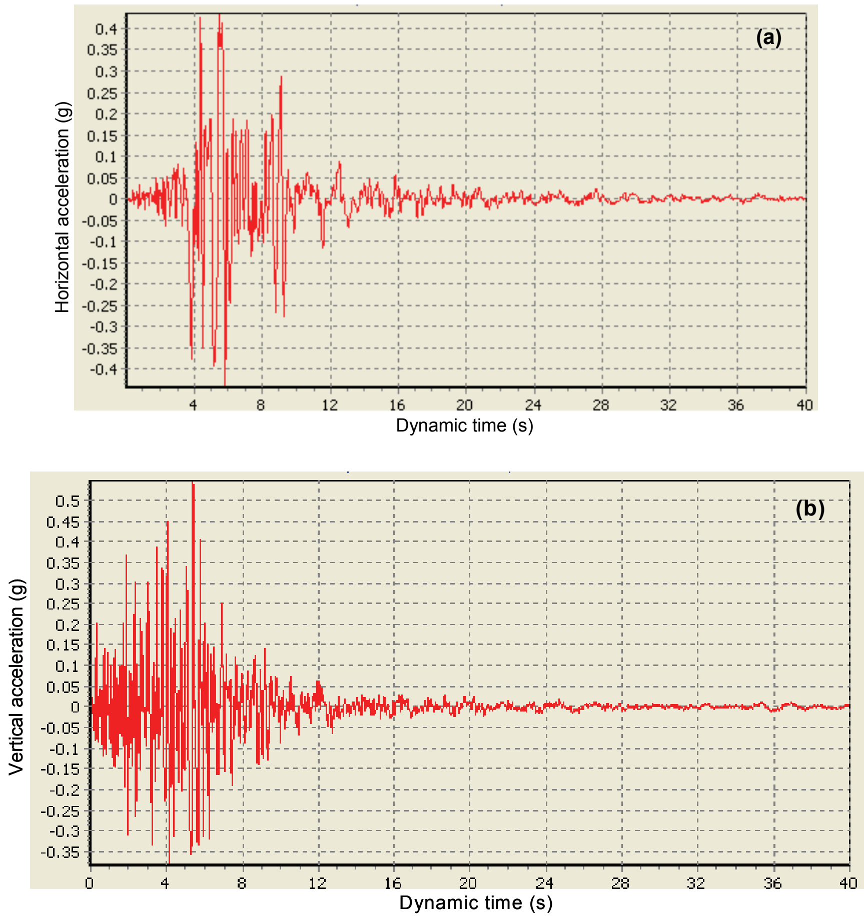

Figure 3. Horizontal (a) and vertical (b) acceleration time histories of the input motions used for the East Azeri NGI slope stability analysis

For the horizontal direction, a site response analysis was performed using the bedrock outcrop motions for this event to compute the motions in the soil profile at the depth corresponding to the base of the PLAXIS model. A similar vertical time history response analysis was carried out in a separate analysis run.

2.4 Monitoring points on the slope (NGI - FE Analysis)

Nodes on the NGI model were monitored to be used as inputs for the displacements to the KBR (Kellogg Brown & Root) FE model. The KBR model was created with nodes coincident with nodal locations of the NGI model in order for the transfer to be undertaken. The nodes which were monitored are indicated on the geometry model in Fig. 2. Also shown on this figure is the location of the EA jacket which is approximately 400m back from the escarpment.

2.5 Details of ABAQUS analysis

2.5.1 Material and pipe sectional properties

Flexible Pipe

Material:	Flexible Armour type
Outer Diameter (O.D.):	296.5mm
Inner Diameter (I.D.)	203.2mm.
Element Type:	b31h.

This is a 2-noded linear beam with hybrid formulation.

2.5.2 Model details

The analysis of the pipeline was carried out with the FE package, ABAQUS. The analysis was carried out in two stages:

Stage 1

1. Settling pipeline on the seabed and applying gravity load.

   To achieve this step, the pipeline is laid out on a dummy flat surface. The dummy flat surface is lowered in stages past the actual seabed surface leaving the pipeline to take up the natural profile of the seabed.

A plot of the pipeline on the seabed with the two surfaces is shown in Fig. 4.

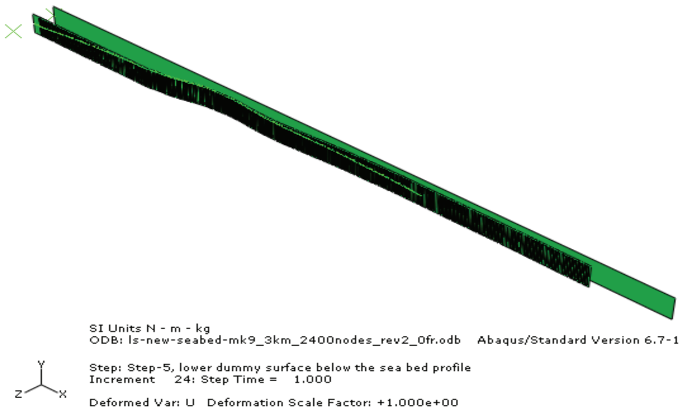

Figure 4. Pipeline laid down on seabed

Note: The flat rigid surface which has been lowered past the sea bed is shown in green; the pipeline is on the seabed in green against the black background. Please note the model has been rotated. The z direction denoted on the axis global axis is vertical.

The pipeline profile in plan is shown in Fig. 5.

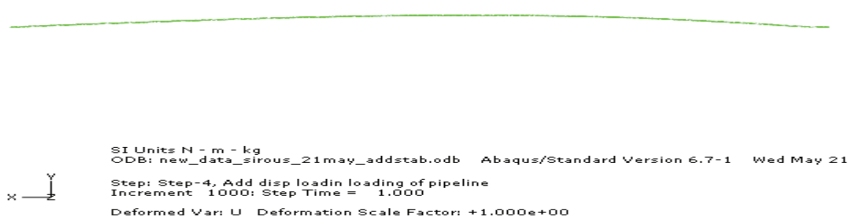

Figure 5. Plan: Pipeline Profile on Seabed (Note it is virtually straight with a very small curvature)

Stage 2

2. When a pipeline is laid on the seabed it will embed itself up to a certain extent within the soil and hence experiences larger frictional resistance during movements due to the increased contact area.

The pipeline is modeled with the updated coordinates from Stage 1, but with three orthogonal springs attached to each node. The springs in three directions provide the frictional resistance in the longitudinal and lateral directions and support resistance in the vertical direction.

The springs attached to the model are shown in Fig. 6 for a small section of the pipeline.

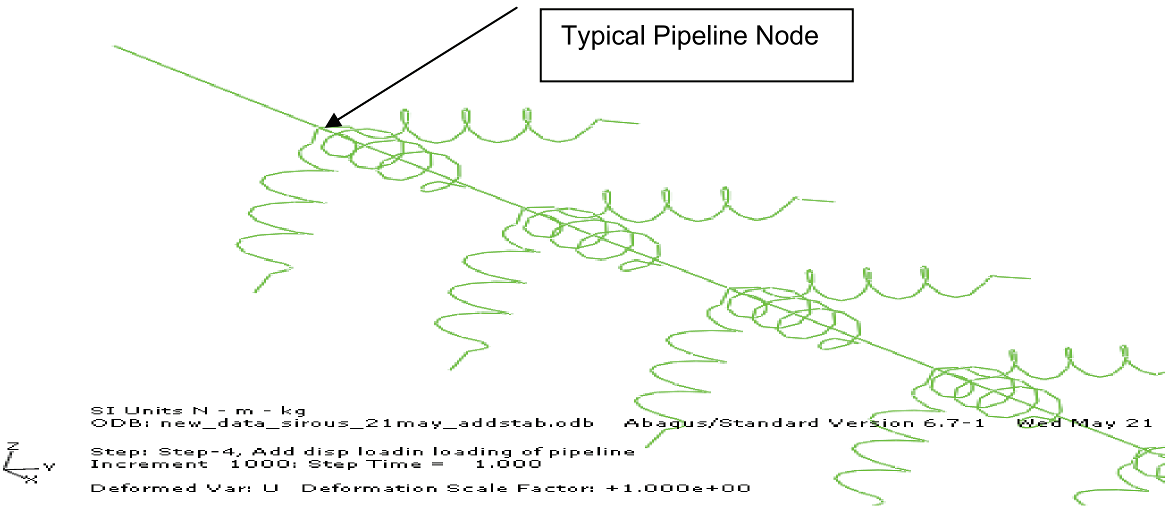

Figure 6 Pipeline with springs (zoomed in for clarity) [Note: Springs are two noded. End 1 attached to the pipe nodes and the other end (end 2) on the ground. Seismic loads are applied at end 2].

2.5.3 Methods of calculating soil spring stiffnesses

The spring stiffness theory calculations used on this study are essentially in-house and the methodology extracted from relevant publications listed in Sec. 7.0.

3.0 ANALYSIS METHOD

Referring to Fig. 2, the distance between 2 successive monitoring points in a horizontal direction was approximately 50m along the slope. In order to model the pipeline in ABAQUS a much finer mesh was used. The distance between successive nodes in the model was 1.25m. The pipeline was modeled starting from the EA jacket to a distance of 3,000m following the seabed profile.

It was decided that to be consistent, displacements occurring at the nodes at a particular snapshot of time were to be used. From visual inspection of time history plots three maximum points in time were selected:

i) 11.8 sec
ii) 18.6 sec
iii) 27.3 sec

The analyses for evaluating loads at the anchor were carried out for the displacements, reported at the above three time steps.

Each PLAXIS node was matched with the nearest ABAQUS node.

3.1 Boundary conditions

The pipeline was anchored at the two ends - the manifold location and jacket location.

3.2 Loading

The input data for seismic loading came from NGI. Horizontal and vertical displacements at the nodes shown in the NGI soil model were extracted from the reported time history data. Referring to Figure 6, two noded springs in the horizontal and vertical directions were modeled and the displacements due to seismic loading were applied to nodes attached to the ground, rather than to the pipe nodes.

A small portion of the pipeline with the springs modeled in the three directions is shown in Fig. 6. The pipeline has 2401 nodes and 2400 elements. Except for the two end nodes (nodes 1 and 2401 with boundary conditions) springs in three directions were modeled in all remaining 2399 nodes. The pipeline in essence is fully supported on springs. For example, when the gravity loading (self-weight) is applied this is taken up by the vertical springs). During application of the seismic loading all three springs are active and displacements (horizontal and vertical).

It is now well known that the friction vs. displacement curve has a sharp peak. In order that the ABAQUS model does not have any convergence problems due the rapid change in values on either side of this peak, the curve near the peak was rounded off; the difference between the original curve and the modified curve is almost imperceptible and therefore there will not be any change in the result.

It should be noted that this measure may not always be necessary.

4.0 RESULTS

The main objective of the analysis was to estimate the maximum reaction at the anchors. This is required for sizing the anchors. The results for the displacements at three time steps are shown in Table 4.1.

Table 4.1. Results for flexible pipe

Time Step (sec) NGI data	**Max Reaction At Anchor (kN)**	**Pipe**	**Comments / Variation**
11.8	**705**	Flexible	Max Axial Stiff
18.6	**715**	Flexible	Max Axial Stiff
27.3	**680**	Flexible	Max Axial Stiff

5.0 Conclusions

The following should be noted:

- This is based on the tentative route adopted by NGI for their FE studies.

- The route takes no mitigation into account – that is that the flow line goes directly to the riser base in a virtually straight route (see Fig. 5) so all axial pull is directly transferred onto the tie-in/anchor point.

- The estimated embedment of the flow line is evaluated at 67mm, the amount of embedment directly influences the amount of frictional area over which the soil drag is passed to the pipeline. Soil springs in direction 2 and 3 are approximate only and further more accurate data for these may become available.

The analysis confirms that the loads at the jacket anchor (given the direct approach) are such that a suitable restraint is required to withstand the load as it is in excess of the capacity of the riser.

There are conservative features built into the model.

1. The loads are based on the maximum axial stiffness. These maximum values result in maximum movement of the pipeline, which in turn generate the maximum loading at the jacket end anchor.

2. The displacements reported by NGI, are for the 3,000 year event and encompass the project design envelope.

3. There are no mitigation measures included in the model.

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REFERENCES

Bruton, D., White, D., Cheuk, C., Bolton, M. and Carr, M. (2006), 'Pipe/Soil Interaction Behaviour During Lateral Buckling, Including Large-Amplitude Cyclic Displacement Tests by Safebuck JIP', OTC 17944, Houston, 2006.

Cathie, D.N., Jaeck, C., Ballard, J.C. and Wintgens, J.F. (2005), 'Pipeline Geotechnics – State-of-the Art', Frontiers in Offshore Geotechnics, ISFOG 2005, Ed. Gourvenec and Cassidy, Taylor & Francis Group, London.

Hill, A.J. and Jacob, H. (2008), 'In-Situ Measurement of Pipe-Soil Interaction in Deep Water', OTC 19528, Offshore Technology Conference, Houston, USA.

Merifield, R. White, D.J. and Randolph, M.F (2008), 'The ultimate undrained resistance of partially embedded pipelines', *Geotechnique,* 58, No. 6, 461-470.

Murff, J.D., Wagner, D.A. and Randolph, M.F. (1989), 'Pipe Penetration in Cohesive Soil', *Geotechnique,* 39, No. 2, 213-229.

Verley, R. and Lund, K.M. (1995), 'A soil resistance model for pipelines placed on clay soils', Proc. Conf. on Offshore, Marine and Arctic Engineering (OMAE), Vol. 5, 225-232.

Wantland, G.M. and O'Neill, W., Reese, L.C. and Kalajian, E.H. (1979), 'Lateral Stability of pipelines in clay', OTC 3477, Houston, 1979.

White, D.J. and Randolph, M. F., (2007), 'Seabed characterisation and models for pipeline soil interaction', *Int. J. Offshore and Polar Engineering*, Vol. 17, No. 3, 193-204.