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EARTHQUAKE-RELATED GEOHAZARDS AND SEISMIC DESIGN OF PIPELINES

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ABSTRACT

As the energy needs are constantly increasing, the optimum engineering design of gas transmission infrastructures, such as onshore or offshore high-pressure gas pipelines, compressor stations, and liquefied natural gas (LNG) terminals is a fundamental step. Since the design should always be cost effective, the term “optimum” is used here to describe the balance between safety and economy. One of the key issues during the design of both pipelines and facilities is the potential ground movements due to various geohazards under static and seismic conditions, such as landslides, ground settlements, active faults, soil liquefaction, etc. According to the current state of practice, there exist various ways to treat potential ground movements. The simplest way is to avoid the problematic (in terms of ground movements) area(s) by rerouting the pipeline or relocating the facility. Since this is not always feasible (due to various technical and/or environmental constraints), the alternative way is to construct the pipeline and/or the facility within the problematic area. In the latter case, the application of various mitigation/protection measures aiming to minimize the ground movements is a straightforward option. On the other hand, a more sophisticated -and possibly more effective- treatment is to verify the pipeline and/or the facility against the expected ground movements (without any mitigation/protection measures), and check whether the developed distress (in terms of strains or stresses) is acceptable or not. It is evident that if the distress is proved to be excessive and inacceptable for the structure or infrastructure under examination, the application of mitigation/protection measures is the one and only solution. Since the engineer should check all feasible solutions depending on the circumstances, compare the associated risk and cost, and propose the optimum solution to the client, the current paper tries to shed some light on the very challenging and tricky issue of the design of gas transmission infrastructures against ground movements.

1. INTRODUCTION

Undoubtedly, the energy needs worldwide are expected to continue to increase, many deposits of hydro-carbons will be discovered and exploited. In addition, as many big cities in developing countries are rapidly expanding, there are also increased demands for lifelines (e.g., water distribution networks) worldwide. As a result, new onshore and offshore pipelines will be designed and constructed for the smooth transfer of oil, gas and water (Psarropoulos et al. 2013).

As any pipeline has to be verified against the distress and ground deformations caused by all potential geohazards (such as slope instabilities, ground failures, etc) as shown in Fig. 1 for

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earthquake-related hazards, it becomes evident that the safety and the integrity of any pipeline are directly related to the identification of geohazards and the realism of their quantitative assessment as demonstrated in related guidelines (JGA 2000; ALA 2002; Eurocode 8 – Part 4 2006; IITK-GSDMA 2007; etc) and studies (Hashash et al. 2001; Ogawa and Koike 2001; O' Rourke and Liu 2012; among others). In areas characterized by moderate to high seismicity (such as Turkey, Greece, Italy, etc), the assessment of all earthquake-related geohazards (such as seismic wave loading, earthquake-triggered landslides, soil liquefaction phenomena, active faults, etc) and the required seismic studies are crucial components of the engineering design of such large-scale infrastructure (Psarropoulos et al. 2013).

In any case, since the earthquake-related geohazards along a pipeline route vary considerably (Fig. 1), their assessment and treatment depend strongly not only on the mechanical and geometrical properties of the pipeline, but on the local site conditions as well. Although in most cases onshore geohazards are fairly similar to offshore geohazards (e.g., landslides, active-fault crossings, soil liquefaction, etc), the assessment and the treatment of offshore geohazards are usually different.

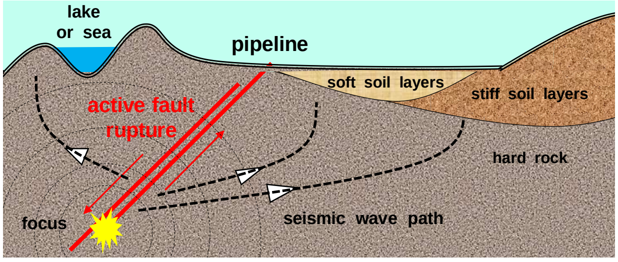

Figure 1. Main types of seismic loading of pipelines: a) ground shaking due to seismic waves and local site conditions earthquake; b) permanent ground deformations due to fault rupture, soil failure, slope instabilities.

As aforementioned, every gas pipeline has to be verified against the potential distress and ground deformations caused by all potential geohazards, thus, it becomes evident that the safety and the integrity of any pipeline are directly related to the identification of geohazards and the realism of their quantitative assessment (Psarropoulos and Antoniou 2013). In areas characterized by moderate to high seismicity, the assessment of all earthquake-related geohazards (such as seismic wave loading, earthquake-triggered landslides, soil-liquefaction phenomena, active faults, etc) and the ensuing seismic studies are crucial components of the engineering design. Nevertheless, since the geomorphological, geological and geotechnical conditions along a pipeline route vary considerably, the geohazard assessment and treatment depend strongly not only on the mechanical and geometrical properties of the pipeline, but on the local site conditions as well. Despite the fact that in most cases onshore geohazards are fairly similar to offshore geohazards (e.g., landslides, active-fault crossings, soil liquefaction, etc), the assessment and especially the treatment of offshore geohazards are usually different.

The optimum engineering design of any gas pipeline is a fundamental step. Since the design should always be cost effective, the term “optimum” is used here to describe the balance between safety and economy. One of the key issues during the design of gas pipelines is the potential ground movements due to various geohazards under static and seismic conditions. According to the current state of practice, there exist various ways to treat potential ground movements. Obviously, the first option is to consider avoiding the problematic (in terms of ground movements) area(s) by rerouting the pipeline (and relocating the connecting facilities). Since this is not always feasible (due to various technical and/or environmental constraints), the alternative way is to construct the pipeline within the problematic area. In the second case, the application of various mitigation/protection measures aiming to minimize the ground movements is a straightforward option (Balis et al. 2013). On the other hand, a more sophisticated treatment is to verify the pipeline against the expected ground movements (without any mitigation/protection measures), and check whether the developed distress (in terms of strains or stresses) is acceptable or not. It is evident that if the distress is proved to be excessive and inacceptable for the pipeline under examination, the application of mitigation/protection measures is the one and only solution.

Moreover, the various facilities of a gas transmission system, such as compressor stations or LNG terminals, comprise of stiff but sensitive structures that usually cannot accommodate substantial levels of ground movements/settlements, especially when the latter are differential. The first part of the paper, after providing an overview of the main onshore and offshore geohazards and the related ground movements, focuses on the similarities and the differences of their assessment, while a discussion is presented regarding the various ways of treatment depending on the circumstances. Emphasis is given on the earthquake-related geohazards, as their quantitative assessment is usually more demanding.

Since the engineer should check all feasible solutions depending on the circumstances, compare the associated risk and cost, and propose the optimum solution to the client, the second part of the paper tries -through a case study- to shed some light on the very challenging and tricky issue of the optimum design of gas transmission infrastructures against ground movements.

2. GEOHAZARDS AND GROUND MOVEMENTS

The term "geohazard" is mainly used to describe the hazard associated with geological and geotechnical features or processes in the vicinity of a planned infrastructure that may pose a threat to the integrity or serviceability of the infrastructure over its design lifetime. Geohazards are identified by studying the geomorphology and geology of a region and through geophysical and geotechnical surveys. Although, the qualitative assessment of geohazards is a straightforward procedure that requires experienced geoscientists, their quantitative assessment (in order to estimate the potential occurrence and evolution of ground movements during the design lifetime of the infrastructure) is a very demanding task that requires, apart from experience, investigations, analyses and interpretation from an engineering point of view.

Depending on the circumstances, the main categorization of geohazards can be the following:

a) natural or man-made,
b) static or dynamic (mainly earthquake-related),
c) onshore and offshore;

while the main types of geohazards are the following:

a) river crossings,
b) various geological/geotechnical phenomena,
c) earthquake-related geohazards.

Therefore, under static conditions, apart from river crossings and buoyancy effects, the main geohazards either onshore or offshore are the following:

a) slope instabilities (such as landslides, creep phenomena, etc),
b) special soils (mainly organic soils, such as turf, etc),
c) karst phenomena,
d) inactive faults,
e) mud volcanoes, and
f) erosion.

Since ground movements during a slope instability may range between few centimetres to many hundreds of meters (or even kilometres in the case of submarine landslides), slope instabilities are regarded as the most challenging cases of geohazard under static conditions. If the ground movements are expected to be excessive, a facility, such a compressor station or a LNG terminal, cannot accommodate these movements, while on the other hand, a flexible gas pipeline crossing an unstable slope may develop strains that remain at an acceptable level.

Additionally, the aforementioned geomorphological and geological conditions, in combination to the active tectonics of areas characterized by moderate or high seismicity, may lead to the following earthquake-related geohazards:

a) strong ground motion,
b) active-fault rupture,
c) various types of earthquake-triggered slope instability,
d) soil-liquefaction phenomena, and

e) tsunamis.

With the exception of tsunamis which may have a direct impact on the seaside facilities, the other earthquake-related geohazards may distress a pipeline or a facility due to strong ground motion and/or permanent ground deformations. Strong ground motion is a dynamic loading as it causes seismic wave loading in the case of pipelines or inertial forces in the case of facilities.

In general, permanent ground deformations are regarded as a more severe type of loading for lifelines than the strong ground motion, since the strains induced by permanent ground deformations may become fairly large. These deformations, that are considered to be quasi-static, may be caused by faulting, slope instabilities, and/or ground movements induced by soil liquefaction phenomena. In the case of a pipeline, the permanent ground deformations may lead to failure either due to tension or buckling. On the other hand, in the case of a facility, permanent ground deformations may cause substantial differential settlements and/or failure of the foundation soil.

2.1 Strong ground motion

Records and analyses in the past have shown that, apart from the soil stratigraphy, the geomorphological and topographical conditions of an area tend to alter the amplitude, frequency content, duration, and spatial variability of the seismic ground motion, and consequently of the seismic loading of any structure (Tsompanakis and Psarropoulos 2012). In seismic analysis and design of important and/or sensitive structures, an amplification study and the corresponding ground response analyses are regarded as a fundamental step for the assessment of the strong ground motion. Especially in the case of long structures, such as pipelines (which usually cross valleys or bathymetric irregularities), the success in calculating the seismic distress depends primarily on the ability of engineers to estimate realistically the level of seismic wave loading on the surrounding soil under “free-field conditions” (i.e., without the existence of the structure).

The dynamic stress field developed in the soil is a function of the characteristics of excitation at the base of the soil deposit and the local site conditions. In general, the term “local site conditions” is being used to describe both ground, geomorphological, and topographical / bathymetrical conditions. The amplification study and the related ground response analyses should be based on the available geophysical / geological / geotechnical studies and surveys (definition of seismic bedrock, soil-profile classification, and soil properties), as well as the seismological data at the seismic bedrock (including peak ground motion parameters, response spectra and accelerogramms).

2.2 Active-fault rupture

Seismic distress may be imposed on engineering structures and infrastructure not only due to strong ground motion, but also due to a fault movement. The vulnerability of various engineering structures to permanent ground displacements resulting from fault movements has been observed during several earthquakes worldwide. Given the pipeline route or the location of the facility, the procedure of identification and quantification of the potentially active faults typically includes the following vtwo basic stages:

a) The first stage consists of the identification of the active fault (if present). In the case of offshore pipelines the identification is based mainly on geophysical surveys and studies, while for an onshore pipeline or facility, the identification is mainly performed via remote-sensing and analysis of topographic and geological data (terrain analysis).

b) The second stage includes the estimation of the expected cumulative offset (measure) of the fault displacement. The anticipated per-event surface displacement is a value that can be obtained by empirical formulas of the literature.

The aforementioned procedure, usually referred to as Tectonic or Seismotectonic Study, provides qualitative and quantitative data for the characterization, in terms of activity, geometry, displacement and kinematics of the identified fault zones. As the soil conditions at the seabed surface or at the ground surface may modify the characteristics of the fault rupture at the bedrock (estimated in the Seismotectonic Study), the assessment of the fault-rupture-propagation path till the surface is required. More specifically, if soil formations cover an active fault, the fault-rupture-propagation path has to be estimated and the permanent deformations imposed to the pipeline or to the facility have to be determined along a wider zone.

It has to be emphasized that an industrial facility has limited capability to withstand the potential permanent deformations at the ground surface induced by the rupture of an active fault, while a pipeline, being more flexible from a structural point of view, is capable to deform until a substantial (but acceptable) level of strain. This means that the detection of an active fault underneath the area of a planned facility may be even prohibitive for the facility, enforcing thus its relocation, while a pipeline may cross the same fault without any damage. In cases where the fault-induced strains of an onshore are excessive, mitigation measures should be adopted, such an increase in pipe wall thickness, reduction of the angle of interface friction between the pipeline and the soil and/or oversized trench filled with a loose to medium granular soil without cobbles or boulders. Nevertheless, in cases where the fault-induced strains to an offshore pipeline are excessive, the re-alignment of the pipeline may be the only robust and safe option.

2.3 Seismic slope instability

Since high-pressure gas pipelines are long structures, their route is expected to cross regions of high risk of landsliding. It is evident that in earthquake-prone areas the risk is higher as a seismic event may increase the driving forces, triggering thus a potential landslide. Consequently, after the identification of these regions during the geological and/or geophysical surveys, the geo-engineer has to: (a) evaluate the slope stability under static conditions, and (b) assess realistically the seismic slope stability.

Seismic slope stability assessment is performed with the application of methods which are grouped according to the adopted mathematical model in three main categories: (a) pseudostatic, (b) permanent deformation or sliding block, and (c) finite element or stress deformation. The simplified pseudostatic methods have prevailed in current engineering practice, partly because of the high complexity of the more elaborate finite element models, which require the definition of stress-strain soil response under cyclic loading. However, the application of such methods is based on certain simplifying assumptions.

In particular, the main issue raised in the pseudostatic methods is the selection of the so-called “seismic coefficient”. The latter is defined as the ratio of the constant seismic force acting on the potential failure surface divided by the weight of the failure wedge. The approximation of a constant seismic coefficient becomes an erroneous selection since:

a) near the slopes the role of topography effects is predominant; hence, the magnitude and the frequency content of the acceleration response time history varies throughout the potential failure surface, and

b) the time-varying nature of the dynamic response indicates that severe loading lasts only instantly.

The conservatism of the method arising from the negligence of both spatial and time variation of the inertia forces was early recognized and seismic coefficients were calibrated to acceptable level of displacements were proposed for dam design. Modern guidelines for the evaluation of seismic induced landslides propose the dependence of the seismic coefficient on the peak ground acceleration at the bedrock, the distance from the seismic source and the acceptable seismic displacements.

The permanent deformation methods are pertinent modifications of the well-known Newmark’s sliding-block approach. This approach is based on the fundamental assumption that stability may be established according to a simple model, which consists of a rigid block on an inclined plane, and therefore displacements are obtained by double integration of the relative acceleration. Relative acceleration is the difference between the applied and the critical (or yield) acceleration, where the latter refers to the value of the acceleration required to approach incipient sliding state, i.e., factor of safety equal to unity. The most influential assumption of this method is the negligence of the flexibility of the sliding mass. Ever since Newmark's pioneer study, two different approaches have been proposed to overcome this limitation: the decoupled procedure where the dynamic response of the examined failure surface is calculated separately from the induced displacements, and the coupled procedure where the dynamic response is considered simultaneously to the permanent displacement development by the direct solution of the governing differential equations.

It has to be stressed that, although in the static slope stability analyses safety factors, FS, lower than 1 are unacceptable (since they correspond to total slope failure in a limit-equilibrium analysis), in the seismic slope stability assessment values of dynamic safety factor, FSd, lower than 1 may be accepted since in most of the cases they do not necessarily imply total failure, but accumulated permanent ground deformations. These deformations may be accepted or not, depending on the circumstances (type of structure, specifications, etc). It is evident that the less the accepted deformation is, the more conservative the design should be. Therefore, performance-based design could be applied (in combination with techno-economic analysis) to achieve a cost-effective solution. Obviously, if zero permanent ground deformations are required for any reason (i.e., requiring a greater dynamic safety factor: $FS_d>1$), the design is expected to be extremely conservative, leading thus to the implementation of very expensive mitigation measures (i.e., slope stabilization).

2.4 Soil liquefaction phenomena

Soil liquefaction is a phenomenon in which cohesionless soil deposits below the groundwater table may lose a substantial amount of strength due to strong ground motion, potentially resulting in reduced bearing capacity of the foundation, lateral spreading, settlements, and other adverse effects. Liquefaction and related phenomena have been responsible for tremendous amounts of damage during many earthquakes worldwide (e.g., Turkey, Japan, New Zealand, etc).

Liquefaction occurs in loose cohesionless fine-grained saturated soils, i.e., soils in which the voids between individual particles are completely filled with water. This water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other. Given that liquefaction is likely to occur at a particular location, it is very important, from an engineering point of view, to predict the amount of horizontal and vertical permanent ground deformations associated with the liquefaction. More details on the estimation of liquefaction-induced permanent ground deformations for pipelines can be found in O' Rourke & Liu (2012).

2.5 Tsunamis

Pipelines near shore and mainly seaside facilities are potentially vulnerable to tsunamis, hence special attention should be given whenever needed to consider this hazard. For instance, as the Mediterranean Sea is characterized by moderate to high seismicity, several tsunamis have been recorded in the past and there are regions that need special attention for constructing any type of lifelines and related infrastructure. Especially at the eastern part of Mediterranean region, which is seismotectonically active and consequently the most tsunamigenic (Psarropoulos et al. 2013). Note also that most of the tsunamis worldwide are attributed to large fault ruptures at the seabed, while few of them are related to extensive submarine landslides.

3. GAS TRANSMISSION INFRASTRUCTURE

3.1 Onshore and offshore pipelines

In areas characterized by terrain and geohazard challenges, the design of any structure or infrastructure is definitely demanding. In the case of onshore and offshore gas pipelines that are long, sensitive and in many cases critical structures, the pipeline verification and the design of any potentially required mitigation measure are prerequisites for the pipeline safety and integrity.

Although the flexibility of the pipelines permits a certain amount of deformation (provided that the potential geohazards and the related ground movements have realistically been assessed), in some cases the geohazard treatment is rather unavoidable. Nevertheless, this is not the case for offshore geohazards due to the high cost of any mitigation measures offshore.

3.2 Compressor stations and LNG terminals

As mentioned before, gas transmission infrastructure include compressor stations and LNG terminals. In most of the cases compressor stations and LNG terminals are usually seaside facilities, in areas that are usually characterized by: (a) poor ground conditions (soft granular soils) and (b) high groundwater tables. In contrast to pipelines, both compressor stations and LNG terminals cannot withstand substantial permanent ground deformations. This means that in the case of a geohazard, such as slope instability, soil liquefaction, fault rupture, etc, there exist two options. The first is to apply mitigation measures that will eliminate the permanent ground deformations, while the second option is to avoid the problematic area relocating the facility. Note that in the case of the rehabilitation of an existing facility, only the first option is feasible.

Since soil liquefaction and lateral spreading are more likely to occur in loose fine-grained saturated soils with poor drainage, the reduction of the liquefaction-induced permanent ground deformations may be achieved by: (a) increasing the density and strength of sandy materials, (b) lowering the ground water level, and/or (c) increasing the dissipation of pore-water pressure. Finally, to reduce the potential for liquefaction, liquefiable soils in the area of the facility could be locally replaced with non-liquefiable materials by the application of stone columns. Nevertheless, these mitigation measures are practical and cost effective only when the liquefiable area is limited and the liquefiable soil layer is relatively close to the ground surface.

In the case of potential slope instability close to the shore or an active fault underneath the facility, mitigation measures could be applied, such as mat foundations, piles, stone columns, various types of retaining structures, etc. However, since the dimensions of the plan view of a facility may be rather extensive, the cost of mitigation measures may be prohibitive. In that case the relocation of the facility could be the most cost-effective option.

4. CASE STUDY: SEISMIC DESIGN OF AN ONSHORE GAS PIPELINE

Since Greece is characterized by the highest seismicity in Europe, the authors have been involved with various projects of geotechnical earthquake engineering, including projects in the oil & gas industry. In the following paragraphs a case study from the oil & gas industry in Greece will be described briefly. It refers to the seismic design of a high-pressure gas pipeline in western Greece. After a thorough geotechnical earthquake engineering study, the gas pipeline has been verified against seismic wave loading, static and seismic slope instability, and fault rupture. In areas where the pipeline distress was excessive, mitigation / protection measures have been proposed.

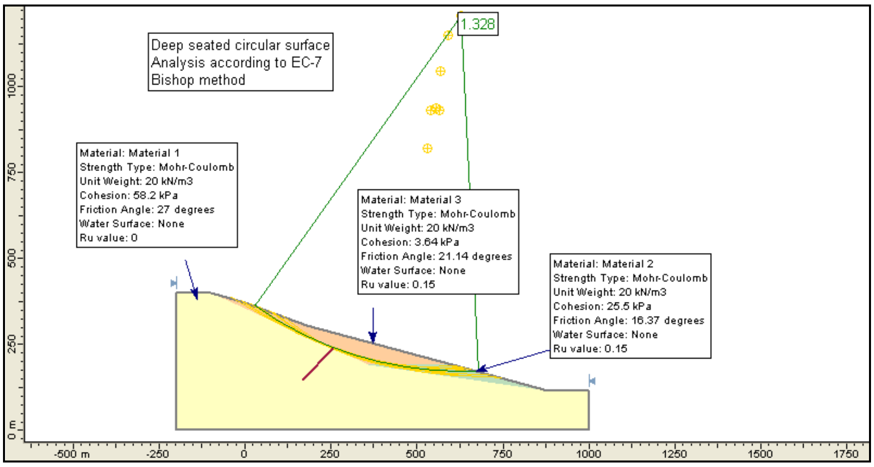

Figure 2. Example of a pipeline founded on a slope. The stability of the slope was verified under static conditions (FS ≈ 1.33)

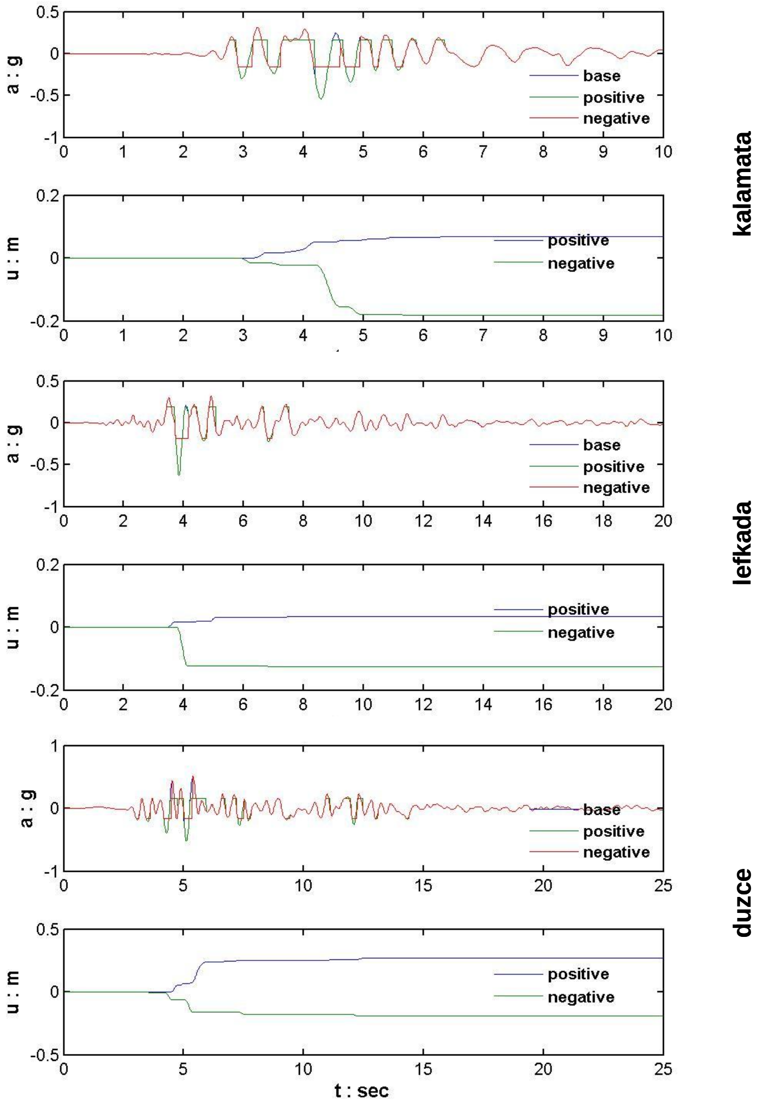

Figure 3. Example of a pipeline founded on the same slope. Time histories of acceleration and permanent displacement for three recorded seismic excitations (Kalamata, Lefkada, Duzce)

One of the most important issues of the seismic design has been the assessment of the dynamic behavior of a slope under strong ground motion in order to verify the ability of the pipeline founded on this slope to withstand any permanent ground deformation at the foundation level. Despite the fact that under static conditions a slope is always designed or checked with factors of safety (FS) that prevent any ground deformation, under seismic conditions Eurocode 8 states that the serviceability limit-state condition should be checked by calculating the permanent displacement of the sliding mass, which means that, depending on the structure, permanent soil deformations due to seismic slope instability may be acceptable at a certain level.

Therefore, given the seismological and the geotechnical data of the area, the geotechnical engineer has to estimate realistically the expected permanent displacements of the slope under seismic conditions. Figs. 2 and 3 present the quantitative hazard assessment of the examined buried pipeline founded on a slope. The first figure (Fig. 2) refers to static conditions where no ground deformation occurred ($FS \approx 1.33 > 1$), while the second figure (Fig. 3) presents the time histories of acceleration and the permanent displacements of the sliding mass in the case of the three different seismic excitations examined. Note that in this specific case all factors of safety under pseudostatic conditions are below 1. The analyses of this specific slope have led to the following conclusions:

a) Regarding the *static slope stability* of the slope, it was concluded that the initial qualitative assessment of the geoscientists that had performed the initial routing was proved to be correct, since the calculated factor of safety under static conditions is regarded as acceptable (>1.3). Nevertheless, given all the various uncertainties of the geometrical and mechanical properties of the ground, in the case that the factor of safety had been calculated between 1 and 1.3, the slope would be regarded as “potentially unstable” with a certain risk of instability.

b) Regarding the *seismic slope stability*, it is evident that if only simplistic pseudo-static analyses had been performed, the slope would have been be characterized as “unstable”, and thus expensive mitigation measures (i.e., stabilization) would have been proposed (since pipeline rerouting is rather impossible for various technical and environmental reasons). The realistic quantitative assessment of the permanent ground deformations and the soil-structure interaction analyses that followed shown that the pipeline can accommodate the anticipated ground movements, and therefore the pipeline can safely cross the potentially unstable area.

In general, after the determination of the hazard, a vulnerability analysis should follow in order to focus both on the effects on the structure itself, and on the primary and secondary consequences on the surrounding environment. The assessment of the effects on the structure requires advanced structural modeling, while geotechnical modeling is also necessary in cases where the soil conditions, the foundation and the soil-structure interaction may be important. In the case of the abovementioned slope and pipeline, given the seismological and the geotechnical data of the area, the engineer, after the estimation of the expected permanent ground displacements of the slope, has to verify the pipeline utilizing a finite-element analysis that will take realistically into account the soil-structure interaction. Note that, if the calculated distress on the pipeline is excessive, the design has to propose mitigation and/or protection measures.

Since active fault is another type of geohazard in the area, Figure 4 illustrates characteristic results of a three-dimensional finite-element simulation which was performed in order to estimate the vulnerability of the examined gas pipeline crossing an active normal fault with a rupture of the order of 0.5 m. Note that, apart from numerical inaccuracies regarding finite element simulations, two main uncertainties are present. The first refers to the mechanical and geometrical properties of the surrounding soil, while the second is related to the ability of the geologists and seismologists to realistically estimate the anticipated fault rupture in the seismotectonic study. For this reason in this case -and since the stains are excessive- an oversized trench filled with a loose to medium granular soil was proposed as a cost-effective mitigation measure.

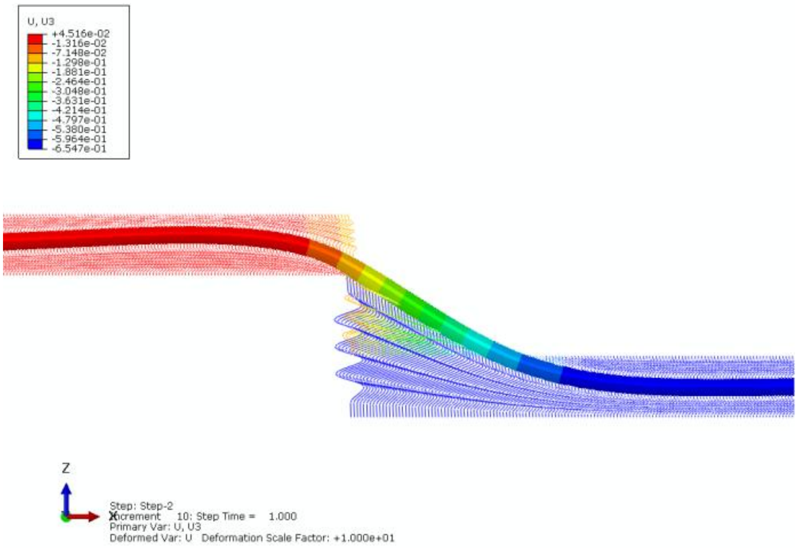

Figure 4. Indicative results of a numerical simulation of a buried pipeline crossing an active fault

5. CONCLUSIONS

In the present work it has been briefly shown that the optimum engineering design of any pipeline is of crucial importance. Since the design should always be cost-effective, the term “optimum” is used to describe the balance between safety and economy. Undoubtedly, one of the key issues during the design of gas transmission infrastructure is the potential ground movements due to various geohazards under static and in some areas under seismic conditions, such as landslides, ground settlements, active faults, soil liquefaction, etc. The qualitative assessment and especially the quantitative assessment of these ground movements is a fundamental step of the design of any type of infrastructure. Given the direct and indirect costs of an unanticipated severe geohazard (in terms of project delays and money), it becomes evident that in areas characterized by terrain and geohazard challenges it is wiser to pay more attention during a medium stage of the design process in order to examine thoroughly alternative ways of geohazard treatment.

According to the current state of practice, there exist certain ways to treat potential large ground deformations. Frequently the first and simpler choice is to avoid the problematic (in terms of ground movements) area(s) by rerouting the pipeline (and relocating the supporting facilities). Nevertheless, the geoscientists and engineers have to examine techno-economically all possible options, namely: (a) avoidance of the problematic area(s) by pipeline rerouting or facility relocation, (b) various mitigation measures aiming to minimize the ground movements to acceptable levels, and (c) crossing through the problematic area(s). The second option is usually the most conservative, but in parallel the most expensive. On the other hand, in the third option, which may be the most cost effective in many cases, the design should take realistically into consideration the local site conditions along with the structural capability of the infrastructure under examination to accommodate the expected ground movements. Apparently in that case, realistic soil-structure-interaction analyses and a detailed monitoring scheme are absolutely required during the design phase and the operation phase, respectively.

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