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MASTER THESIS

OFFSHORE PIPELINES CROSSING ACTIVE SEISMIC FAULTS

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Abstract

Nowadays, the exploitation of hydrocarbons reserves in deep seas and oceans, in combination with the need to transport hydrocarbons among countries, has made the design, construction and operation of offshore pipelines very significant. Under this perspective, it is evident that many more offshore pipelines are expected to be constructed in the near future and in particular in the wider Mediterranean region. Given the fact that offshore pipelines are crossing extended areas, they may face a variety of geo-hazards that cause substantial permanent ground deformations and potentially threaten the integrity of the pipeline.

The present study focuses on the impact of permanent ground deformations induced by active seismic faults on offshore pipelines. For this purpose, a numerical simulation (through finite-element modeling and strain-based criteria) is made, in order to study the distress of offshore pipelines subjected to PGDs induced by active normal and reverse seismic faults at the seabed. Factors, such as the geometrical properties of the fault, the mechanical properties of the ruptured soil formations, and the pipeline characteristics, are examined.

Beginning with an extended introduction to the subject, by presenting some general aspects of offshore pipelines and marine geo-hazards, the problem under investigation and the motivation of the study are explained. Subsequently the geo-hazard of seismic faults is further analyzed as well as the special seismic characteristics of the Mediterranean region. After a literature review on similar researches, a validation of the numerical model, developed in the present study, is performed, through the comparison of the numerical results with the analytical predictions of another study. Having validated the numerical model, a range of critical parameters is examined and their impact on the pipeline is presented. After some interesting conclusions regarding the seismic vulnerability of offshore pipelines, potential cost-effective mitigation measures are proposed taking into account constructability issues.

Περίληψη

Σήμερα η εξόρυξη αποθεμάτων υδρογονανθράκων, σε μεγάλα βάθη θαλασσών και ωκεανών, σε συνδυασμό με την ανάγκη για μεταφορά των υδρογονανθράκων μεταξύ χωρών, έχει καταστήσει το σχεδιασμό, την κατασκευή και τη λειτουργία των υποθαλάσσιων αγωγών εξαιρετικά σημαντική. Υπό αυτό το πρίσμα, είναι φανερό ότι πολλοί περισσότεροι υποθαλάσσιοι αγωγοί πρόκειται να κατασκευαστούν στο εγγύς μέλλον και συγκεκριμένα στην ευρύτερη περιοχή της Μεσογείου. Δεδομένου ότι οι υποθαλάσσιοι αγωγοί διανύουν εκτενείς περιοχές, είναι πιθανόν να αντιμετωπίσουν μία ποκιλία γεω-κινδύνων οι οποίοι προκαλούν σημαντικές μόνιμες εδαφικές παραμορφώσεις και πιθανόν να απειλήσουν την ακεραιότητα του αγωγού.

Η παρούσα Διπλωματική εργασία έχει ως αντικείμενο τη διερεύνηση της επιρροής ενεργών σεισμικών ρηγμάτων σε αγωγούς υδρογονανθράκων. Για το σκοπό αυτό χρησιμοποιείται κώδικας πεπερασμένων στοιχείων με τον οποίο προσομοιώνεται η επίδραση της κινηματικής του ρήγματος στον αγωγό και εξετάζεται η καταπόνηση των αγωγών όταν αυτοί υπόκεινται σε μόνιμες εδαφικές μετακινήσεις που εκδηλώνονται στο έδαφος ή στον πυθμένα της θάλασσας μετά από την ενεργοποίηση κανονικού και ανάστροφου σεισμικού ρήγματος. Μελετούνται διάφορες παράμετροι που επηρεάζουν το πρόβλημα, όπως ιδιότητες ρηγμάτων, γεωμετρικά χαρακτηριστικά, μηχανικές ιδιότητες υλικών κ.α.

Αρχικά γίνεται μια εκετεταμένη εισαγωγή στο υπο μελέτη πρόβλημα, παρουσιάζοντας κάποια γενικά στοιχεία για υποθαλάσσιους αγωγούς και θαλάσσιους γεω-κινδύνους. Στη συνέχεια αναλύεται εκτενέστερα ο γεω-κίνδυνος των σεισμικών ρηγμάτων και γίνεται μια σύντομη ανασκόπηση των σεισμοτεκτονικών δεδομένων της περιοχής της Μεσογείου. Μετά από μια βιβλιογραφική ανασκόπηση, γίνεται η επαλήθευση του αριθμητικού μοντέλου που αναπτύχθηκε στην παρούσα μελέτη, μέσω της σύγκρισης των αριθμητικών αποτελεσμάτων με τις αντίστοιχες αναλυτικές λύσεις, από άλλη ερευνητική μελέτη. Έπειτα, μία σειρά από κρίσιμες παραμέτρους εξετάζονται και παρουσιάζεται η επιρροή τους στον αγωγό. Τέλος, καταβάλλεται προσπάθεια αξιολόγησης των αποτελεσμάτων της μελέτης προκειμένου να εκτιμηθεί το μέγεθος των προβλημάτων και να προταθούν δυνητικά μέτρα αντιμετώπισής τους.

1. Introduction

1.1 Introduction and study motivation

The extensive use of pipelines for transportation of hydrocarbons has been extremely significant during the last decades. Nowadays, the need to transport hydrocarbons among countries, as well as the exploitation of hydrocarbons reserves in deep seas and oceans, have made the use of offshore pipelines more appealing because they are more energy efficient than competing means of transportation. Therefore, the design, construction and operation of offshore pipelines are currently very substantial. Under this perspective, it is evident that many more offshore pipelines are expected to be constructed in the near future, with some already announced to be in the process of design or construction.

Since offshore pipelines are usually crossing extended areas, they may face a variety of geo-hazards that impose substantial permanent ground deformations (PGDs) to the pipeline and potentially threaten its integrity. In case of a geo-hazard area, there exist three options to proceed. The first option is to avoid the problematic area through rerouting, which is usually regarded as an unfavorable solution due to its high cost and the great loss of time, both extremely important for such projects. The second is to apply (if possible) mitigation/protection measures in order to eliminate the geo-hazard itself, an option difficult to apply in great depth. Finally, the last appealing option is to allow the pipeline crossing through the geo-hazard area, provided that the pipeline will have been verified against the expected PGDs.

In areas with moderate or high seismicity the design of an offshore pipeline is more demanding due to the earthquake-related geo-hazards, such as landslides, soil liquefaction phenomena, and active faults. It is worthy to mention that although worldwide there is a great experience in offshore geotechnics and pipeline design, the experience in seismic design of offshore pipelines is rather limited due to the fact that most of the pipelines have been constructed in non-seismic regions (e.g. North Sea, West Australia, Gulf of Mexico, etc.). Thus, the seismic design of offshore pipelines against active faults requires special attention and further research.

The current study focuses on the seismic design of offshore pipelines against active normal and reverse seismic faults. After an extensive literature review of the provisions of the seismic norms worldwide and of the available analytical methods, the study simulates numerically (through finite-element modeling and strain-based criteria) the distress of offshore pipelines subjected to PGDs induced by active seismic faults at the seabed. Factors, such as the geometrical properties of the fault, the mechanical properties of the ruptured soil formations, and the pipeline characteristics, are examined. After some interesting conclusions regarding the seismic vulnerability of offshore pipelines, potential cost-effective mitigation measures are proposed taking into account constructability issues.

1.2 Offshore pipelines

Although offshore oil and gas production was conducted throughout the entire 20th century, the industry’s importance and vitality did not start until the early 1970s, when the North Sea became a major producer. Since then, there has been a continuous and rapid expansion of the offshore oil industry into many parts of the world. This growth has created the need of a gradual movement to increasingly deeper waters and thus to much more challenging engineering aspects. Although offshore pipelines require significant initial investment, they have a lifespan of up to 40 years and require relatively minor maintenance. Oil and natural gas pipelines are usually the longest, often crossing country and sometimes continental borders.

Some major offshore pipeline projects in the wider European region are the Nord Stream, the Trans Adriatic Pipeline (TAP), the Nabucco pipeline, the South Stream, the Trans-Anatolia gas pipeline and the Interconnector Turkey-Greece-Italy (ITGI) pipeline system (Fig. 1.1). Due to the fact that such major projects require investments of billions of dollars, and in addition can be contentious, they can change entirely or even be cancelled at any moment.

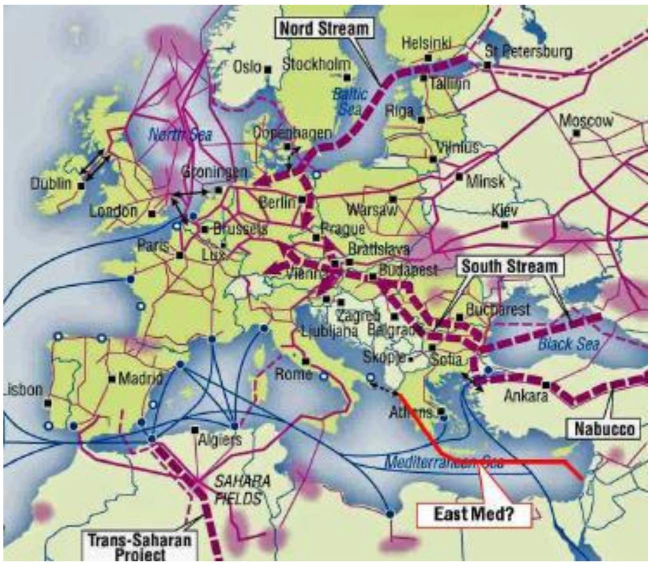


Fig. 1.1 Existing and planned natural gas pipeline projects in the wider European region

Offshore pipelines can be classified as follows Fig. 1.2):

1. Flowlines transporting oil and/or gas from satellite subsea wells to subsea manifolds;
2. Flowlines transporting oil and/or gas from subsea manifolds to production facility platforms;
3. Infield flowlines transporting oil and/or gas between production facility platforms;
4. Export pipelines transporting oil and/or gas from production facility platforms to shore;
5. Flowlines transporting water or chemicals from production facility platforms, through subsea injection manifolds, to injection wellheads.

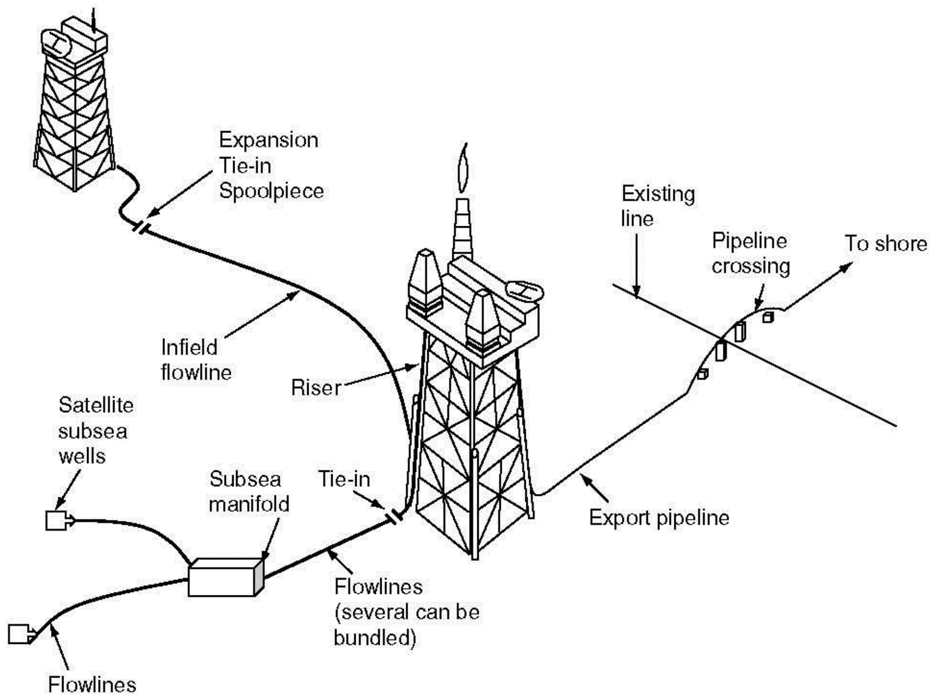


Fig. 1.2 Uses of offshore pipelines [Guo B., Song S., Chacko J., Ghalambor A., (2005)]

Design of offshore pipelines is usually carried out in three stages:

a. conceptual engineering;
b. preliminary engineering and
c. detail engineering.

During the conceptual engineering stage, issues of technical feasibility and constraints on the system design and construction are addressed. Potential difficulties are revealed and non-viable options are eliminated. Required information for the forthcoming design and construction are identified. The outcome of the conceptual engineering allows for scheduling of development and a rough estimate of associated cost.

The preliminary or basic engineering defines the pipeline design so that system concept is fixed (pipeline size, grade and wall thickness), prepares authority applications, and provides design details sufficient to order the pipeline and verified against design and code requirements for installation, commissioning and operation.

In the detail engineering phase, the design is completed in sufficient detail to define the technical input for all procurement and construction tendering. The primary objectives can be summarized as:

- Route optimization;
- Selection of wall thickness and coating;
- Confirm code requirements on strength, Vortex-Induced Vibrations (VIV), on-bottom stability, global buckling and installation;
- Confirm the design and/or perform additional design as defined in the preliminary engineering;
- Development of the design and drawings in sufficient detail for the subsea scope. This may include pipelines, tie-ins, crossings, span corrections, risers, shore approaches, subsea structures;

- Prepare detailed alignment sheets based on most recent survey data;
- Preparation of specifications, typically covering materials, cost applications, construction activities (i.e. pipelay, survey, welding, riser installations, spoolpiece installation, subsea tie-ins, subsea structure installation) and commissioning (i.e. flooding, pigging, hydrotest, cleaning, drying);
- Prepare material take off (MTO) and compile necessary requisition information for the procurement of materials;
- Prepare design data and other information required for the certification authorities.

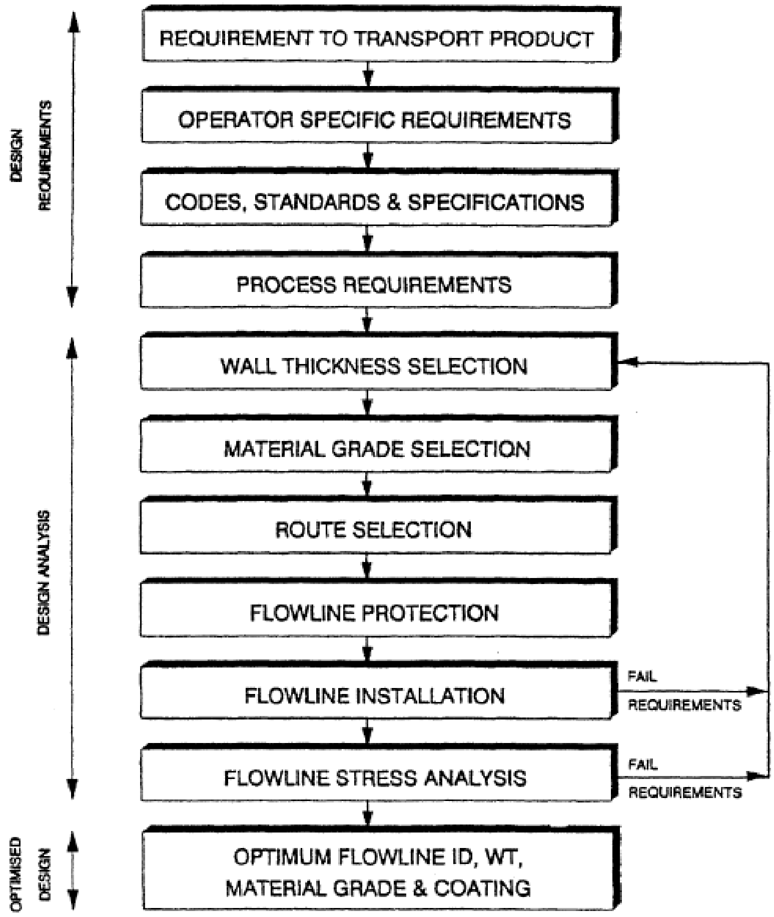


Fig. 1.3 Flowline design process [Bai Y., Bai Q., (2005)].

The bases for design consist of the basic requirements to functionality, as well as a description of the environment into which the pipeline will be placed, leading to the selection of pipeline dimension and routing. A large number of requirements may be included in the bases for design. These comprise the physical pipe properties, such as diameter, steel grade selection based on stress analyses and pipeline specification details, including supplementary requirements to codes and guidelines. Equally fundamental is the definition of parameters regarding flow assurance and pressure containment, i.e. design temperature and pressure, maximum and minimum operating temperature, maximum operating pressure, and details of incidental operation. Other factors include corrosion allowance, sweet or sour service, pipeline protection principles, and possibly a number of design philosophy statements, where the use of proven technology is often specified. In order to optimize the pipeline size parameters the design process required is an iterative one and is summarize in Fig. 1.3.

A pipeline evidently has to be strong enough to withstand all the loads that will be subjected to, both during its construction and operation. During construction it will be bent and pulled and twisted. When it goes into operation, it will be loaded by internal pressure from the fluid it is carrying, by external pressure from the sea, and by stresses induced by temperature changes. Sometimes it may be loaded by external impacts from anchors and fishing gear. Loads on an offshore pipeline, can be divided into the following categories:

- *Functional loads*, which are defined as actions resulting from the operation of the pipeline. They include the effects of: a) internal static pressure, b) pressure surge, c) operational temperature;
- *Environmental loads*, which are defined as normal actions from the natural environment. These include: a) self-weight b) buoyancy c) hydrostatic pressure, d) wave and current loads e) soil pressure / friction;
- *Accidental loads* which are defined as infrequent actions due to natural hazards or third party influence. These hazards may include all kinds of geo-hazards and other hazards derived from fishing activities, shipping, military activities and dropped objects;
- *Installation loads* which are defined as actions incurred during construction of the pipeline.

The distinction is not always obvious, and different national and international codes employ different classifications. Thus self-weight, buoyancy, hydrostatic pressure and soil reactions, which here are considered environmental loads, are classified as functional loads by DNV OS-F101. Actions from fishing activities are treated as accidental loads, but could also be considered functional or even environmental loads. Hydrostatic testing of the pipeline is an installation load, but could also be considered to be a functional load.

1.3 Geo-hazards

The wide areas that offshore pipelines are usually crossing, depending on the prevailing geomorphological and geological conditions, may present a variety of geo-hazards. Geo-hazards are hazards associated with geological or geotechnical features or processes in the vicinity of a planned offshore structure that may pose a threat to the integrity or serviceability of the structure and its foundations over its design lifetime. Geo-hazards are identified by a study of the geology, geomorphology, and geography of a region, and through geophysical and geotechnical surveys and investigations. Fig. 1.4a shows a well-used depiction of typical geo-hazards to be considered by the geotechnical engineer, including many geological features as well as landslides, carbonate sands, unconsolidated soils, gas hydrates, and disturbed sediments. Fig. 1.4b shows another view considering deeper water.

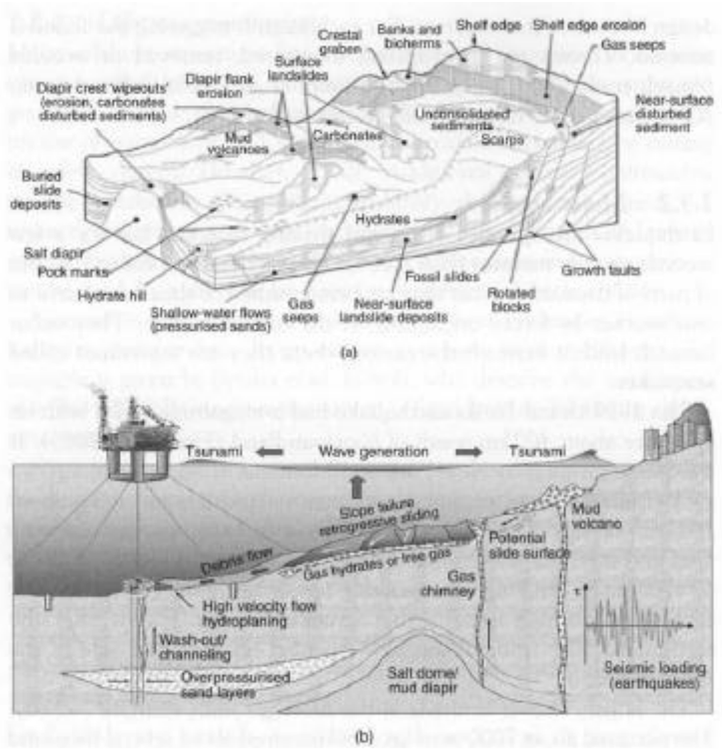


Fig. 1.4 Aspects of geohazards and their management. (a) A widely used summary of deepwater geohazards [Power et al., Offshore Technology Conference, (2005)] (b) More geohazards [Strout and Tjelta, Offshore Technology Conference, (2007)]

Pipelines can be damaged either by permanent movements of ground (i.e., PGD) or by transient seismic wave propagation. Permanent ground movements include surface faulting (Fig. 1.6), settlements or lateral spreading due to soil liquefaction phenomena and land sliding. Despite the fact that PGD hazards exist in small regions within the pipeline network, they may impose large deformations to the pipe and therefore affect the whole network with detrimental consequences. On the other hand, the wave propagation hazards typically affect the whole pipeline network, but with lower damage rates (i.e., lower pipe breaks and leaks per unit of pipe). Thus, the quantitative assessment of a geo-hazard and the evaluation of the associated risk for the pipeline are undoubtedly very important issues of the pipeline design.

Submarine slope instabilities, are caused mainly by earthquake shaking or storm waves, although they can also be triggered by underwater mud volcanoes and slow events involving deposition of material on the upper surfaces of slopes, or erosion by current or other actions (including construction works) on slopes or at their bases. For storm wave induced landslides, they can build up over time in and outside river estuaries, due to deposition of sediment as the velocity of the water slows as it enters the ocean (Fig. 1.5). Rapid sedimentation in these areas result in very weak seafloor and near seafloor soils. Slopes steepen over time, eventually reaching a height and steepness that causes the slope to fail.

Lateral spreads develop when a loose saturated sandy soil deposit liquefies due to seismic shaking. The increase in pore water pressure resulting from the liquefaction process causes non cohesive soil to lose its shear strength, which in turn results in the flow or lateral movement of soil.

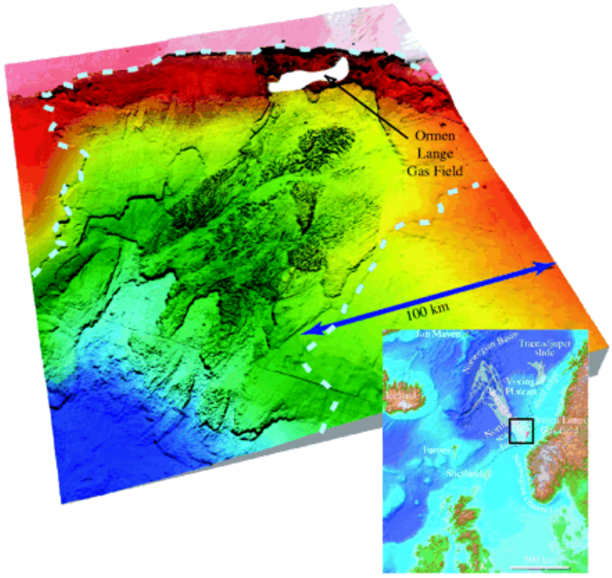


Fig. 1.5 The submarine Storegga slide in the Norwegian Sea

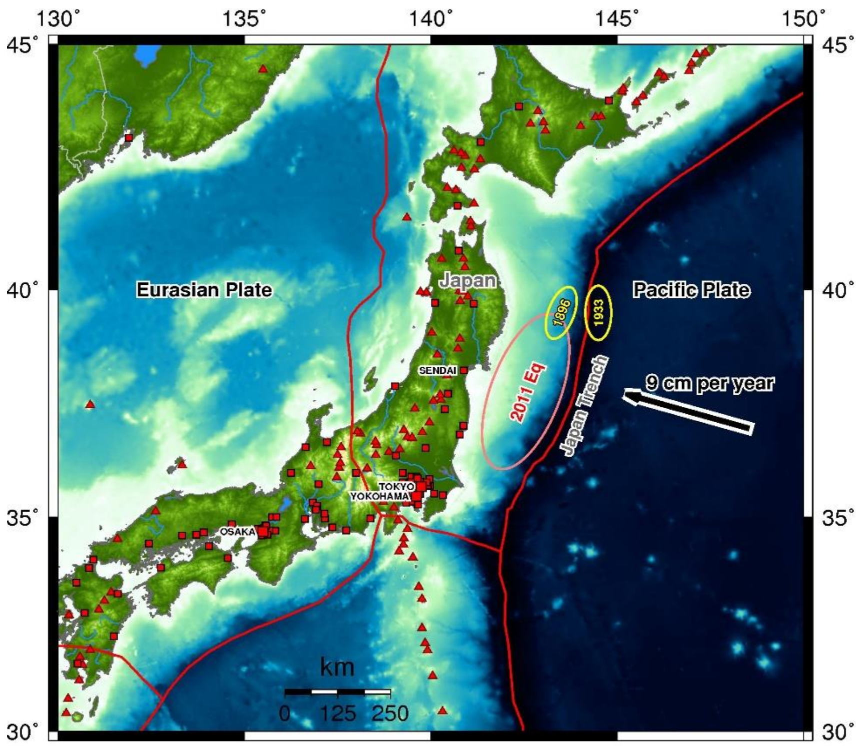


Fig. 1.6 The subduction zone between Pacific and Eurasian plates

The subject of the present study is the geo-hazard of active seismic faults, the permanent ground deformations that are caused by the fault rupture and how the pipeline is affected. In chapter 2, faults and fault propagation path are further discussed.

1.4 Case histories

In many cases in the past, extensive damages to pipelines due to surface faulting have been observed during previous earthquakes, demonstrating the vulnerability of onshore pipelines to PGDs. Examples of documented pipeline damage, regardless its use and material, include: the 1905 San Francisco, 1933 Long Beach, 1952 Kern Country, 1964 Alaska, 1964 Niigata, 1971 San Fernando, 1979 Imperial Valley, 1987 Ecuador, 1989 Loma Prieta, 1990 Manjil Earthquake, 1991 Costa Rica, 1994 Northridge, 1995 Kobe, 1999 Chi-Chi, 1999 Izmit (Kocaeli), 2010 Chile, 2010-2011 Christchurch and 2011 Japan.

Regarding offshore pipelines crossing active faults, one of the most interesting case studies is the case of the Japan-Sakhalin Gas Pipeline, which connects the Russian Sakhalin islands with the Tokyo area through the Japan Sea, crossing the Hokkaido Island (Japan) and the Pacific Ocean, as shown in Fig. 1.7. This pipeline is 1100 km long, of which about 1000 km is offshore and the rest onshore. The steel pipes of 65 to 70 cm diameter are resting on the seabed or buried in the ground, in the active seismic zone along the Pacific Ocean, and are able to deliver about 800 million cubic feet natural gas per day.

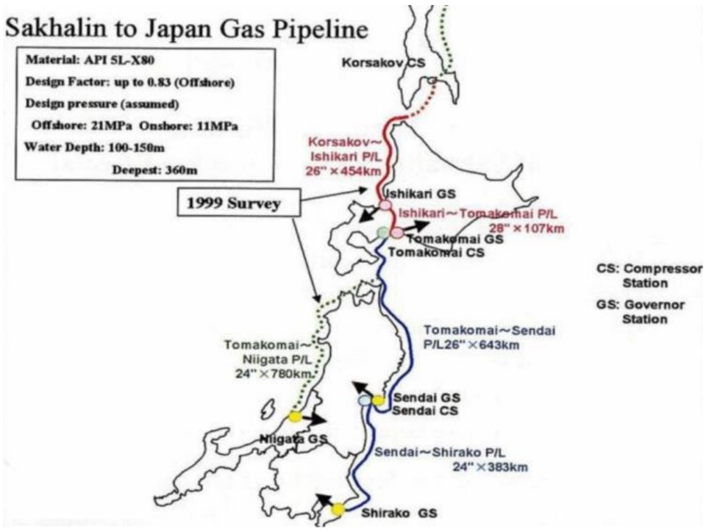


Fig. 1.7 Japan-Sakhalin Gas Pipeline [Hamada, (2003)]

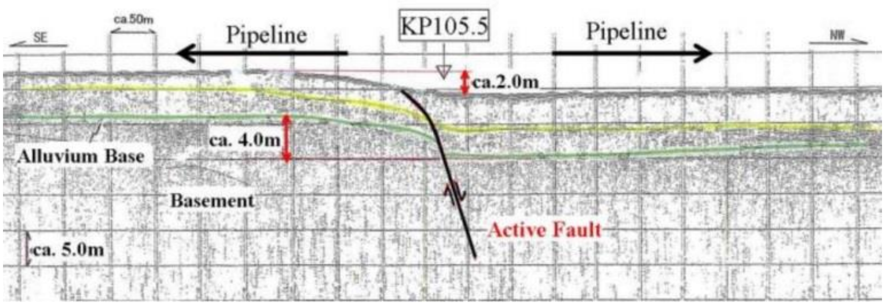


Fig. 1.8 Intersection of the Japan-Sakhalin Gas pipeline with an active normal fault offshore of Chiba prefecture to the east of Tokyo [Hamada, (2003)]

After the initial routing of the pipeline, which aimed in the avoidance of any active faults, another more detailed route survey revealed that the designed pipeline route intersects with three active faults. The pipeline crosses an active normal fault (Fig. 1.8) off Chiba prefecture, where an approximately 2 meter vertical seabed displacement was detected and the average displacement rate has been estimated 22cm/1000 years. The only information from the route survey is about the vertical fault movement, while information about movement in the horizontal direction is not available (Fig. 1.8).

2. Active seismic faults

2.1 Fault Terminology

A *fault* is a planar discontinuity between blocks of rock that have been displaced past one another, in a direction parallel to the discontinuity. A *fault zone* is a tabular region containing many parallel or anastomosing faults. A *shear zone* is a zone across which blocks of rock have been displaced in a fault like manner, but without prominent development of visible faults (Fig. 2. 1Fig. 2. 1 (a) Fault (b) Fault zone (c) Shear zone [Hobbs B., Means W., Williams P., (1976)]). Shear zones are thus regions of localized ductile deformation, in contrast to fault zones that are regions of localized brittle deformation. Another distinction is that the normal component of displacement, which is negligible for faults and fault zones, may ne appreciable for shear zones. The displacement across a shear zone can be inclined at any angle, other than 90^o, to the boundaries of the zone.

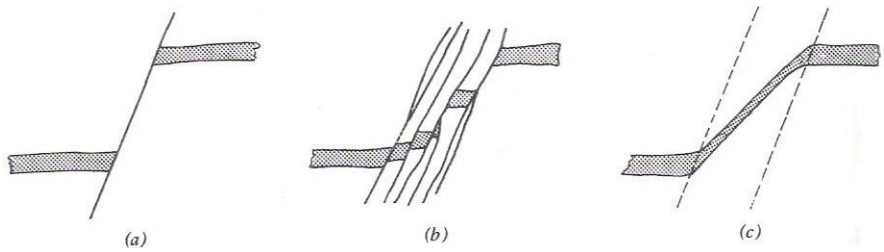


Fig. 2. 1 (a) Fault (b) Fault zone (c) Shear zone [Hobbs B., Means W., Williams P., (1976)]

The rock immediately above and below any non-vertical fault is referred to, respectively, as the *hanging wall* and the *footwall* of the fault (Fig. 2. 2). The displacement vector connecting originally contiguous points in the hanging wall and footwall is called the *net slip*. The components of the net slip parallel to the strike and dip slip of the fault are the *strike slip* and the *dip slip*.

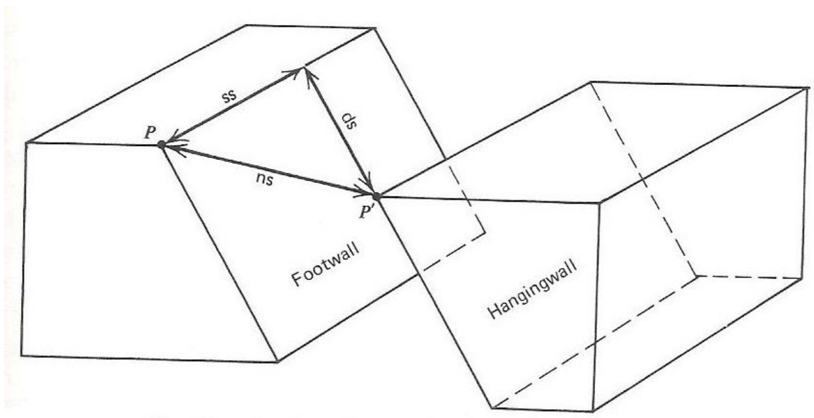


Fig. 2. 2 Terminology for fault displacements. Net slip (ns), strike slip (ss), dip slip (ds). The fault is an oblique-slip fault with normal and sinistral components of dip slip and strike slip displacement, respectively. Before faulting, points P and P' were coincident. [Hobbs B., Means W., Williams P., (1976)]

A fault with dominant strike slip displacement is called a *strike slip fault*. A fault with dominant dip slip displacement is a *dip slip fault*. The sense of the strike slip part of displacement on a fault is described by the terms *sinistral* and *dextral*, or alternatively, *left lateral* and *right lateral*. A fault is sinistral or left lateral if, to an observer standing on one block and facing the other, the opposite block appears to have been displaced to his left.

Faults dipping more or less than 45^o are called, respectively, *high angle faults* and *low angle faults*. A *normal fault* is a high angle, dip slip fault on which the hanging wall has moved down relative to the footwall. A fault of similar type but with a dip less than 45^o is sometimes called a *lag* [Rickard (1972)]. A *reverse fault* is a dip slip fault, either high or low angle [Gill (1971)], on which the hanging wall has moved up relative to the footwall. The terms normal fault and reverse fault, while strictly defined for faults with zero strike slip displacement, can also be used for faults with small strike slip displacements accompanying much larger dip slip displacements [Rickard (1972)]. Where the strike slip and dip slip displacements are similar in magnitude, the fault can be called an *oblique slip fault*. A *thrust fault* is a low-angle reverse fault, according to one common usage [Dennis (1967)]. The term is also used by many geologists for low angle faults that are presumed to have involved reverse dip slip displacement but where this has not been demonstrated (Fig. 2. 3).

A *fault scarp* is a cliff or a steep slope formed by displacement of the ground surface. A *graben* is a fault block, generally long and narrow, that has been dropped down relative to the adjacent blocks by movement along the bounding faults (Fig. 2. 4).

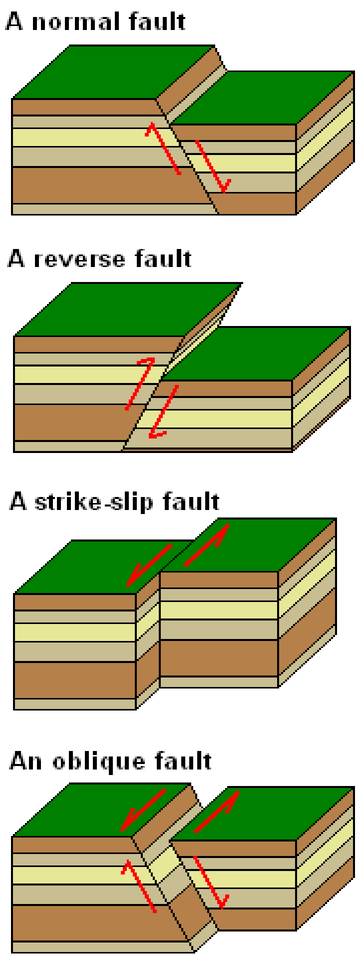


Fig. 2. 3 Types of faults

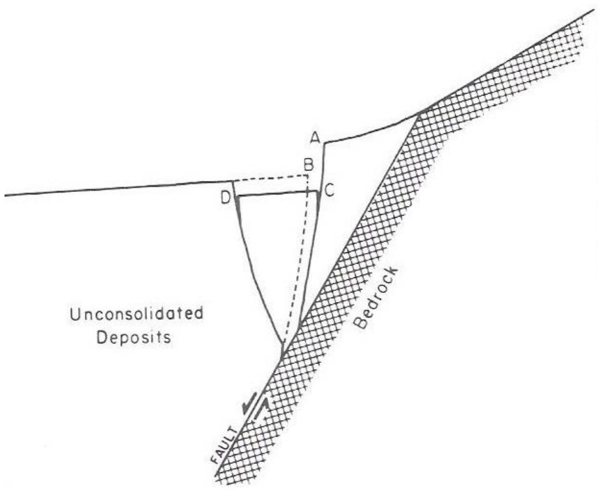


Fig. 2. 4 Cross section of a gravity graben associated with a normal fault. The relative movement of the fault is shown by arrows [Bonilla, (1970)].

Active faults are classified based on their recent activities (Table I). For example, the extent of fault displacement averaged over the recent 1,000 years, S, is a good parameter [Matsuda, (1975)]. Different types of fault classification are possible based on the time of its most recent movement (in the historical era, Quaternary period, or pre-Quaternary), frequency of its movement (number of fault action in the past thousands of years or so), or certainty of being an active fault (lineament that appears similar to fault-induced topography, however, may be formed due to river erosion and geological conditions).

TABLE I
CLASSIFICATION OF ACTIVE FAULTS BASED ON RATE OF DISPLACEMENT
(after Matsuda, 1975)

CLASS	**S** (= Displacement/ 1,000 years)
AA	100 m > S ≥ 10 m
A	10 m > S ≥ 1 m
B	100 cm > S ≥ 10 cm
C	10 cm > S ≥ 1 cm
D	1 cm > S ≥ 0.1 cm

Note: Class AA was added later to the original idea by Matsuda

Fault ruptures may consist of a single narrow main break, but commonly they are much more complex and are accompanied by subsidiary breaks. Bonilla (1970) classifies surface ruptures into three categories or zones. The subsidiary faults can be subdivided into branch faults and secondary faults, the main fault constituting the third category. Fig. 2. 5 shows this classification using some of the surface faulting that accompanied the Fairview Peak, Nevada, earthquake of 1954. The main fault and closely associated faults which, at a map scale of 1:250,000, form a band of varied width, constitute zone I. For this classification the fault with the greatest displacement, length and continuity at the surface is considered the main fault for a particular episode of faulting. Zone II contains the branch faults; these diverge from and extend well beyond the main zone of faults. They either join the main fault at the surface or can reasonably be inferred to do so underground. The distinction between the main fault and branch faults is, of necessity, somewhat arbitrary and often difficult to make. The secondary faults that make up zone III have no surface connection with the main fault.

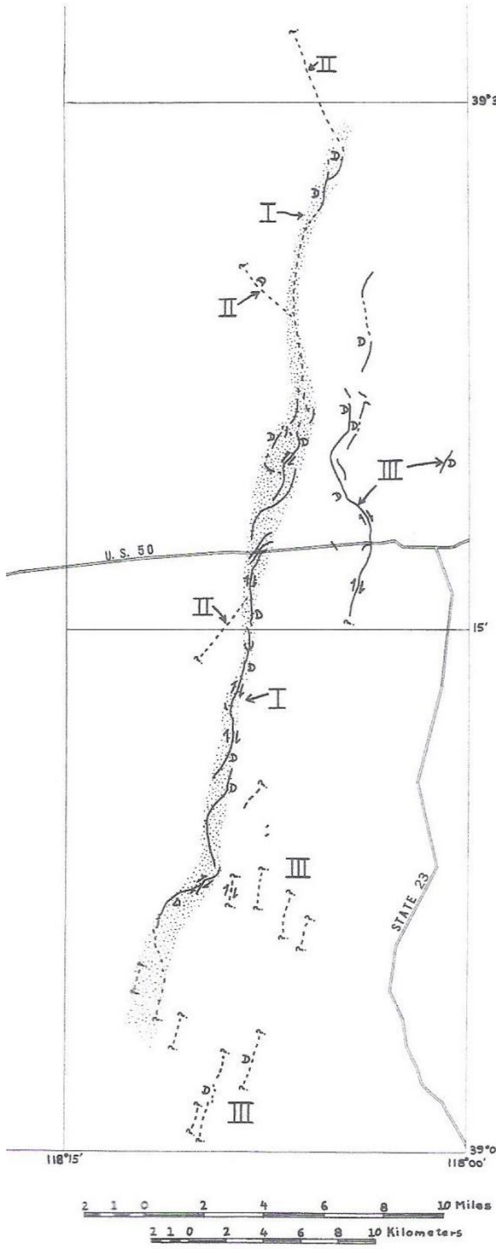


Fig. 2. 5 Map of part of the Fairview Peak, Nevada, 1954, faulting, showing main fault zone (I), branch faults (II), and secondary faults (III). The dashed line indicates faults seen from a distance or interpreted from aerial photographs; the query (?) indicates that the end of break was not determined; D indicates the downthrown side; the single-barbed arrow indicates the relative horizontal displacement. Modifies after Slemmons, 1957 [Bonilla, (1970)].

2.2 Fault propagation path

In a seismic event, the rupture of an earthquake fault generates two types of ground displacement: permanent quasi-static offsets on the fault itself, and transient dynamic oscillations away from the fault.

One of the important problems concerning faults is the prediction of the location and magnitude of surface rupture induced by fault action in the base rock. Along the surface break of the faults, ruptures are neither continuous, nor do they follow precisely the surface outcrop of pre-existing faults. Instead, they follow planes of weakness within a rather broad shear zone. Thus, predicting the exact location of a fault break-out on the surface is a challenging task, even when on a large scale map the fault line is depicted clearly.

The propagation of the fault rupture from the base rock to the ground surface generally depends on:

- the orientation of the fault plane,
- the types of fault movement,
- the amount of fault displacement, and
- the depth and character of the overlying earth deposit.

In fact, the most reasonably consistent patterns of behavior emerge during the review of the case histories. Although exceptions to these general problems of behavior may be found, the majority of evidence justifies making a number of salient observations regarding "typical" patterns of behavior. Diagrams that illustrate these typical characteristics of fault rupture propagation, based on observations made of documented fault rupture case histories, are presented in Figs 2.6 - 2.8. These figures focus on only three of the more important variables: the type of fault movement, the inclination of the fault plane, and the nature of the overlying soil deposit [Bray et al., 1994].

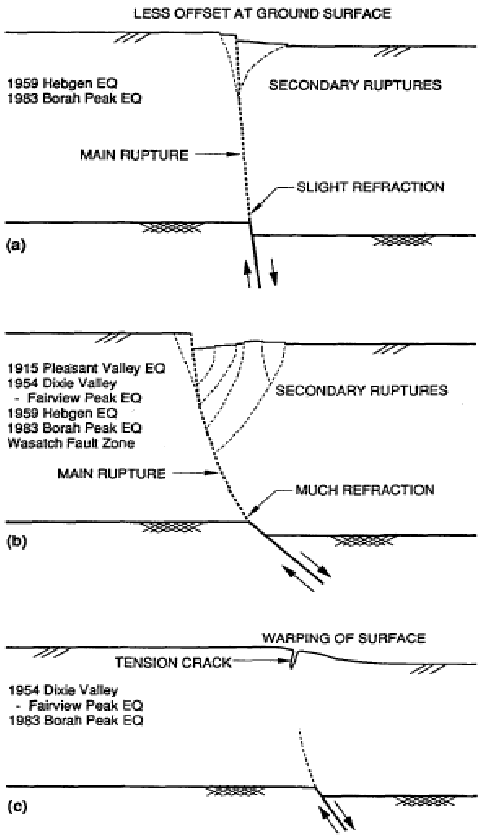


Fig. 2. 6 Path of Normal Fault Rupture through Soil: (a) Stiff Earth Materials, Steep Dip; (b) Stiff Earth Materials, Shallow Dip; (c) Ductile Earth Materials [Bray et al., (1994)]

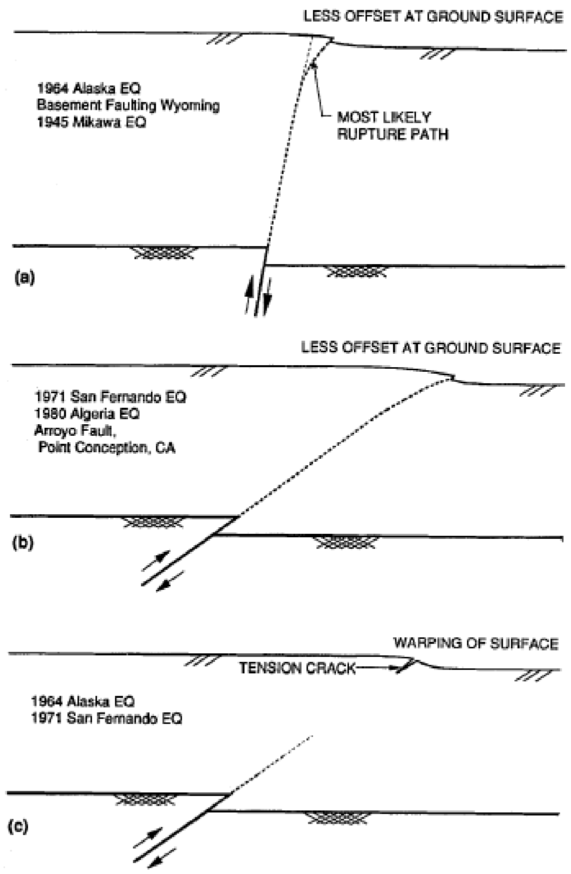


Fig. 2. 7 Path of Reverse Fault Rupture through Soil: (a) Stiff Earth Materials, Steep Dip; (b) Stiff Earth Materials, Shallow Dip; (c) Ductile Earth Materials [Bray et al., (1994)]

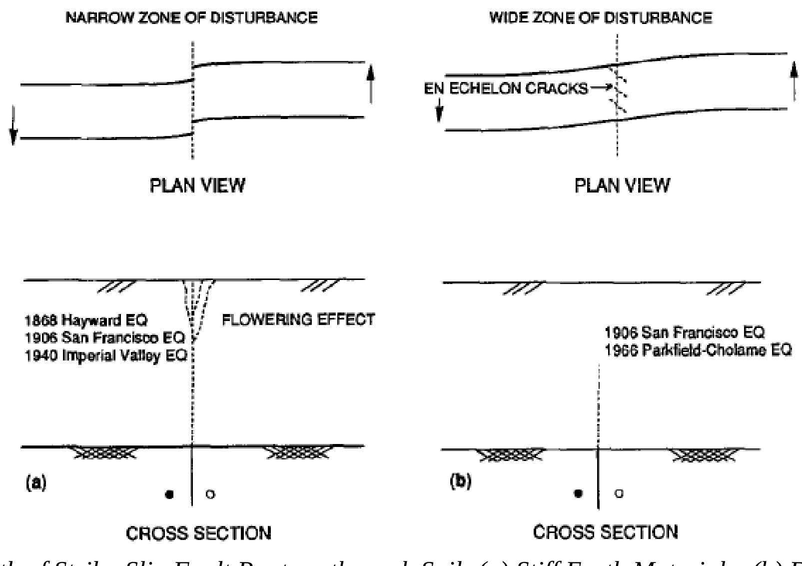


Fig. 2. 8 Path of Strike-Slip Fault Rupture through Soil: (a) Stiff Earth Materials; (b) Ductile Earth Materials [Bray et al., (1994)]

In normal faulting (Fig. 2. 6), the footwall remains intact with most of the deformation being concentrated within the hanging wall. Refraction takes place at the soil-bedrock interface and as the rupture propagates to the surface, it bends over the hanging wall, further increasing its dip. As a result, it may outcrop vertically, or produce gravity grabens. When the fault dip angle θ is small: $\theta \leq 45^o + \psi/2$, an antithetic secondary rupture and a gravity graben are formed. Increasing the dilation, the width of the graben tends to decrease. Once failure occurs, differential movement is usually localized to thin, distinct failure planes. Ductile materials, however, tend to spread the deformation to wider zones and may accommodate significant fault movement by warping without actually developing distinct shear surfaces.

Reverse fault ruptures (Fig. 2. 7) tend to bend over the footwall while propagating to the surface, decreasing their dip. As in the case of normal faulting, ductile earth materials, bending over the slip line, are found to spread the deformation over wider zones. At the maximum bending location, tensile cracking as well as secondary normal-type faulting are observed. Down-warping of the up thrown block during reverse faulting may create tension fissures in the bedrock surface.

Strike-slip faults (Fig. 2. 8), although being significantly different compared to the dip slip faulting mechanism, do possess qualitatively similar characteristics. In most cases, the dip angle is practically vertical, and the deformation is distributed to both sides. Small deviations in the orientation and dip angle of the fault can lead to a truly complicated outcropping pattern. Secondary bedrock deformations are generally less likely to occur in strike-slip faulting. Nevertheless, some amount of secondary movement can occur on existing planes of weakness in the foundation rock during all types of fault movement. In some cases the rupture tends to divert from its vertical slip line, in the means of the “flowering effect”. This effect is usually observed when the rupture propagates through stiff material, as depicted in Fig. 2. 8 [Bray et al., 1994].

In all cases the relative displacement at the fault scarp tends to be smaller than the bedrock fault displacement. Indeed, in some cases the rupture may not even reach the surface. An exception to this, in normal faulting only, is the case when an antithetic secondary rupture and a gravity graben are formed. Then the displacement at the surface may be even higher than at the bedrock.

According to field observations and physical model test results, the differential movement across the fault rupture dissipates as the fault rupture propagates upwards toward the surface through unconsolidated earth materials. Less bedrock fault movement is required to propagate the shear rupture to the ground surface through a layer of relatively brittle material than ductile material. Model testing of anchors in soft clay indicates that the amount of anchor plate displacement necessary to produce failure in the soil above the anchor was primarily dependent on the soil's failure strain.

A majority of the soil overlying the undisturbed bedrock adjacent to the fault does not participate in the rupture process. Most of the soil deposit remains relatively undisturbed, and relative motion is primarily concentrated within a fairly narrow zone above the bedrock fault. Once failure occurs, a majority of the differential movement is usually localized to thin, distinct failure planes. Ductile materials, however, may accommodate significant fault movement by warping without actually breaking.

On one hand, a majority of the differential movement across a fault zone is likely to be concentrated on a single break so that the problem is likely to be localized. On the other hand, the remainder of the movement can occur on secondary fractures or faults some distance away from the main trace, so that the engineer cannot afford to focus exclusively on the main fault trace. Bonilla (1970) found that displacement on secondary fractures could be as much as 20% of the amount of displacement on the main fault as far away as 12 km from the main fault. Thus, in seismic regions, the potential for secondary movements on inactive faults, bedding planes, or existing fractures cannot be ignored. In summary, any existing plane of weakness might be suspect when evaluating the potential for ground movement at a project site.

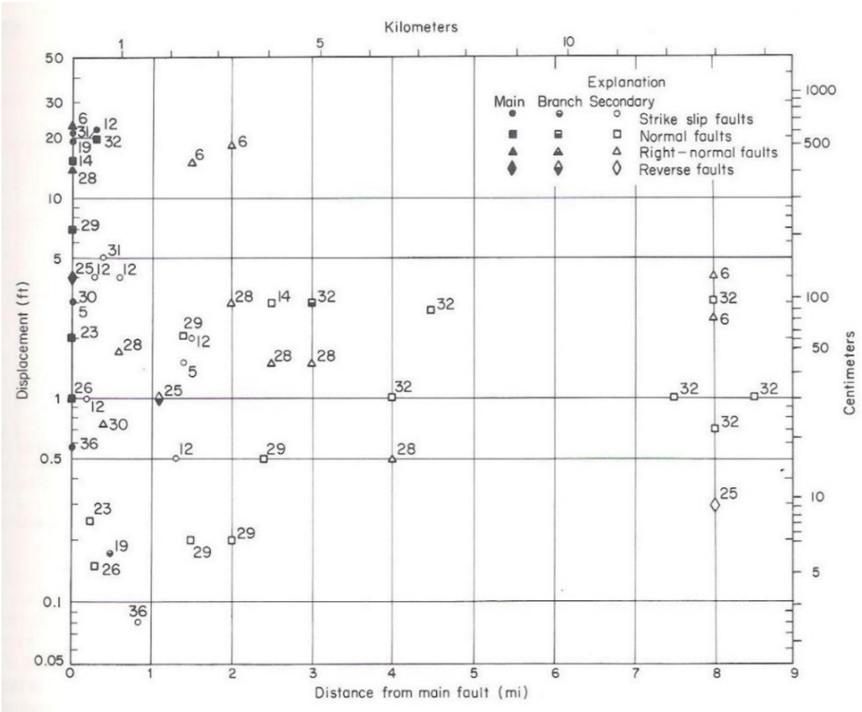


Fig. 2. 9 Fault displacement as related to the distance from the main fault [Bonilla, (1970)].

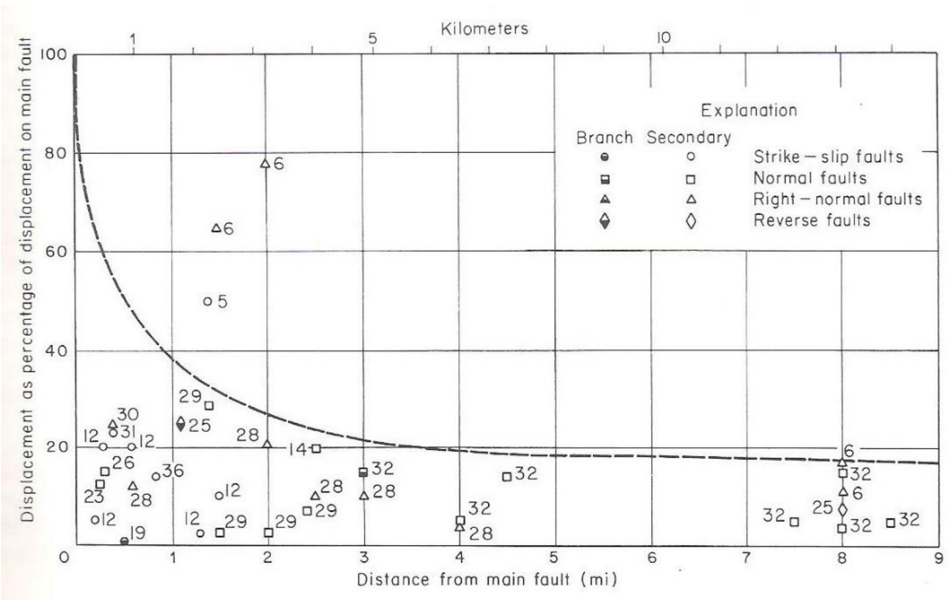


Fig. 2. 10 Fault displacement (in percent of displacement on main fault) as related to distance from the main fault [Bonilla, (1970)].

2.3 Active tectonics of the Eastern Mediterranean region

So far, the transportation of hydrocarbons to Central and Northern Europe is being performed mainly by high-pressure onshore pipelines coming primarily from Central Asia. In the next decades the increased demand for energy in European countries will undoubtedly require the smooth and safe transfer of hydrocarbons from the East Mediterranean, Middle East and North Africa. This process is expected to be performed using offshore pipeline networks and seaside facilities connecting various countries in the Mediterranean Sea and more possibly in the Eastern Mediterranean region (Fig. 2. 11).

However, the Mediterranean basin is characterized by moderate to high seismicity, therefore the design and construction of any infrastructure in this area is much more demanding. The Eastern Mediterranean region defines the region lying between the Caspian Sea and the Adriatic Sea through Caucasus, Anatolia, Aegean Sea and Greece, and it is one of the world’s most seismically active regions.

Fig. 2. 11 Existing and planned onshore and offshore pipelines in Europe and North Africa.

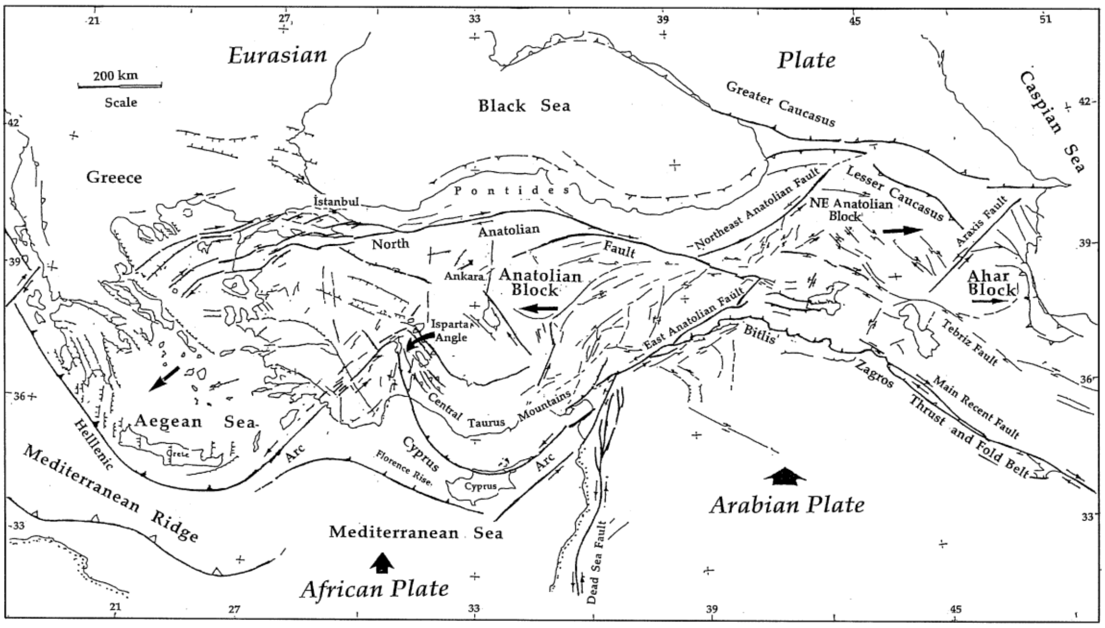


Fig. 2. 12 Distribution of active faults in the Anatolian region [Barka A. and Reilinger R., (1997)]

The tectonics of the Mediterranean region are complex as there were the tectonic break-up and then collision of the African and Eurasian plates in this area. The geomorphology of the Mediterranean Sea, the complexity of its geological structure and the active tectonics have determined the seismicity of the region, leading to natural disasters with great losses of life and property. Fig. 2.13 presents the lithospheric plates in the Mediterranean region.

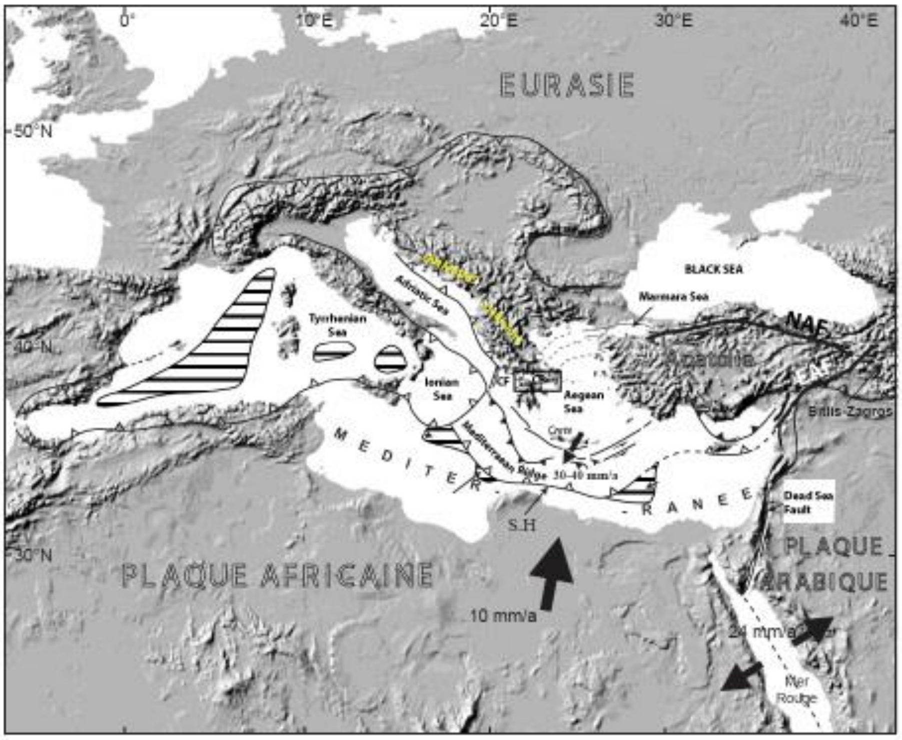


Fig. 2. 13 Lithospheric plates in the wider Mediterranean region. [Barka A. and Reilinger R., (1997)]

Fig. 2. 14 Geodynamic map of the Mediterranean region.

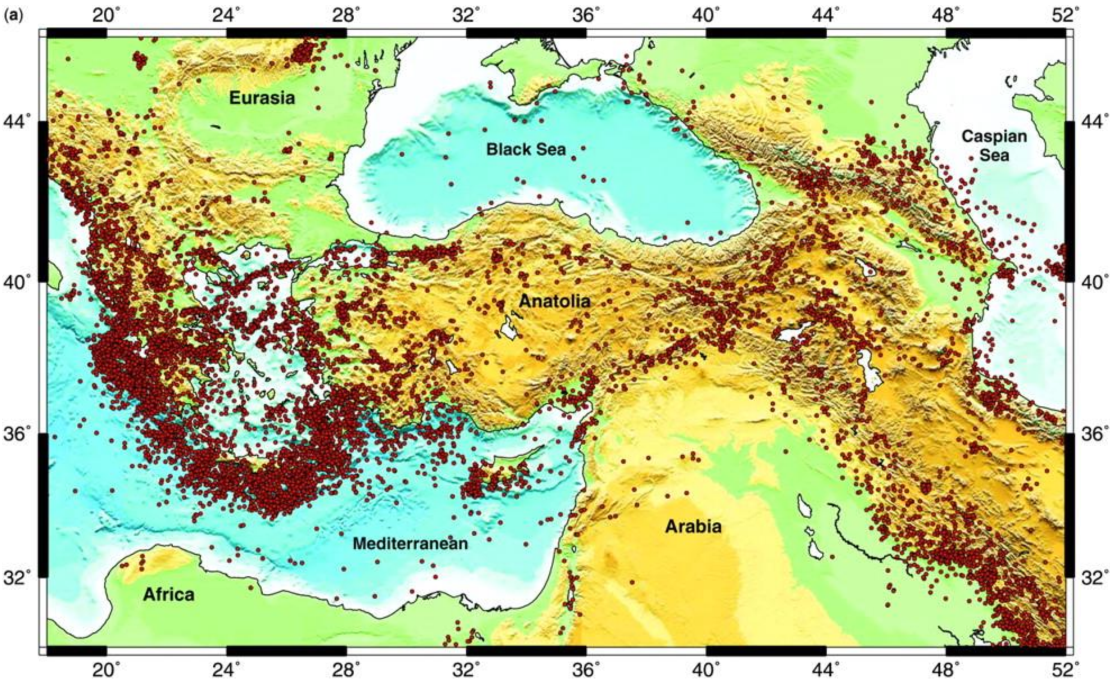


Fig. 2. 15 Seismicity of the Eastern Mediterranean region and surroundings reported by USGS–NEIC during 1973-2007 with magnitudes for M>3 superimposed on a shaded relief map derived from the GTOPO-30 Global Topography Data taken after USGS. Bathymetry data are derived from GEBCO/97–BODC, provided by GEBCO (1997) and Smith & Sandwell (1997a, b)

It is obvious that in this region Greece and Turkey are characterized by the highest seismicity due to the plate tectonics in Eastern Mediterranean: (a) the subduction of the African plate underneath the Eurasian plate, causing the majority of seismic events in the Greek territory, and (b) the horizontal movement of the Anatolian plate towards the west, causing the strike-slip North Anatolian Fault and consequently the high seismicity in Northern Turkey (Fig. 2. 14, Fig. 2. 15, Fig. 2. 16).

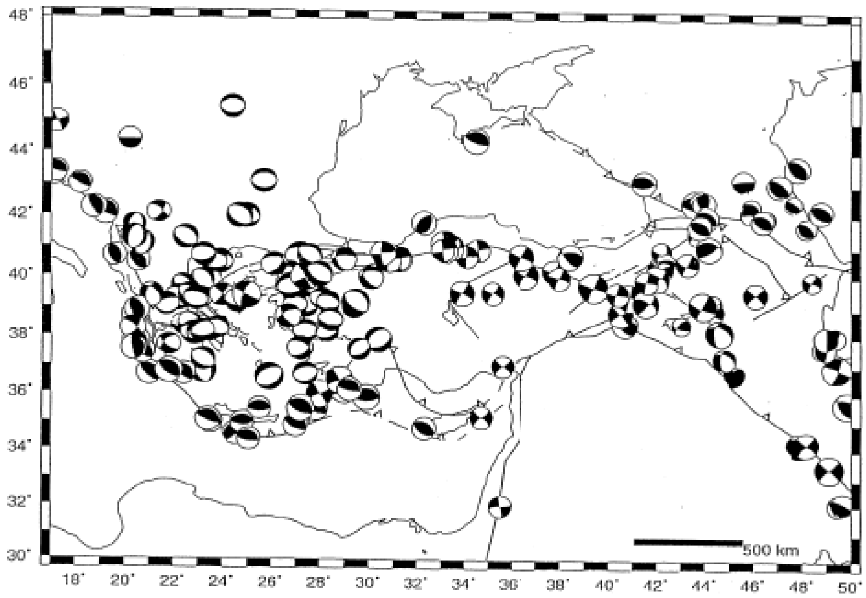


Fig. 2. 16 Distribution of fault plane solutions in the Eastern Mediterranean region, documented from McKenzie (1972, 1978), Jackson and McKenzie (1984) [Barka A. and Reilinger R., (1997)]

The main tectonic elements in the Eastern Mediterranean region are reviewed below:

1. *The Northeast Anatolian fault zone*

The Northeast Anatolian fault zone extends from near the city of Erzurum, Turkey north-east to the Caucasus Mountains. This fault zone consists of several segments with a total length of approximately 350 km.

2. *The Isparta angle*

The Isparta Angle constitutes the junction between the Cyprus and Hellenic arcs and is a tectonic assemblage which has a complex tectonic history. This zone consists of several different tectonic entities.

3. *Cyprus arc*

Subduction along the Cyprus arc has been a long discussed controversial subject in the literature. The occurrence of subduction is not clear south of Cyprus.

4. *Western Anatolia*

In Western Anatolia, E-W and WNW-ESE trending grabens and the related normal faults are the dominant neo-tectonic features. A number of major normal fault events occurred along these faults, for example 1899 Büyük Menderes, 1928 Torbali, 1955 Balat, 1969 Alaşehir, 1969 Simav, 1970 Gediz and 1995 Dinar earthquakes (e.g. Ambrasseys, 1988).

5. *The Hellenic arc*

The Hellenic arc is an arcuate tectonic feature of the eastern Mediterranean Sea related to the subduction of the African Plate beneath the Aegean Sea Plate. It consists of an oceanic trench, the Hellenic trench, on its outer side; two arcs—a non-volcanic outer arc and an inner volcanic arc, the South Aegean Volcanic Arc; and a marginal sea on its inner side.

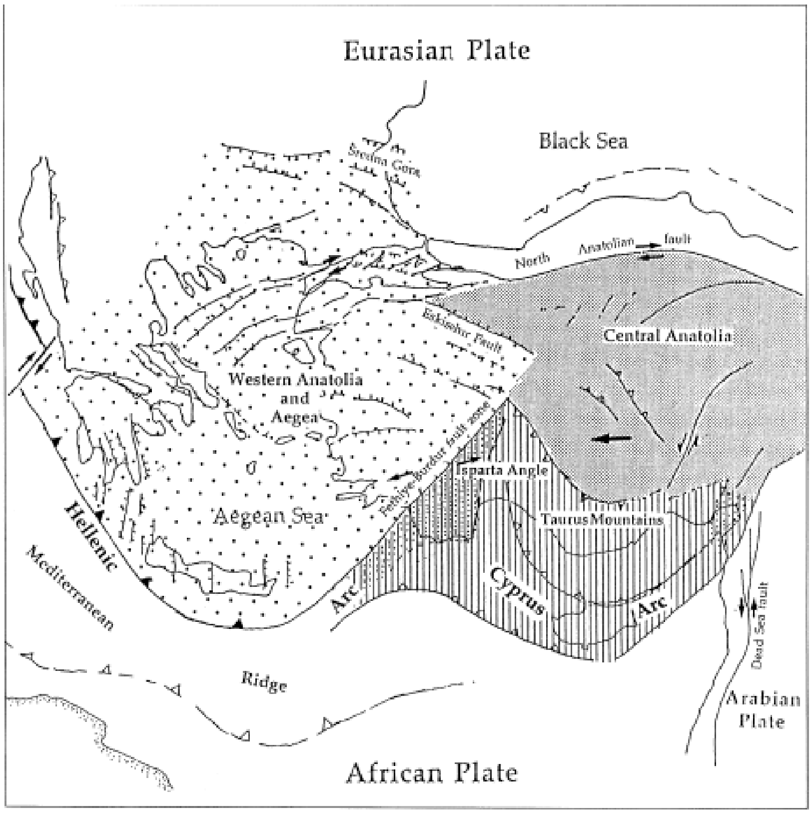


Fig. 2. 17 Neotectonic sub-division of the Anatolian Block. Dotted zones indicate NE-SW extension, shaded area is Central Anatolia where NNE-SSW shortening currently occurs, the hatched area correspond to the complex structures of the Cyprian arc, within this, dotted parts are the extensional areas (belonging to the western flank of the Isparta Angle). Otherwise it represents compressional tectonics. [Barka A. and Reilinger R., (1997)]

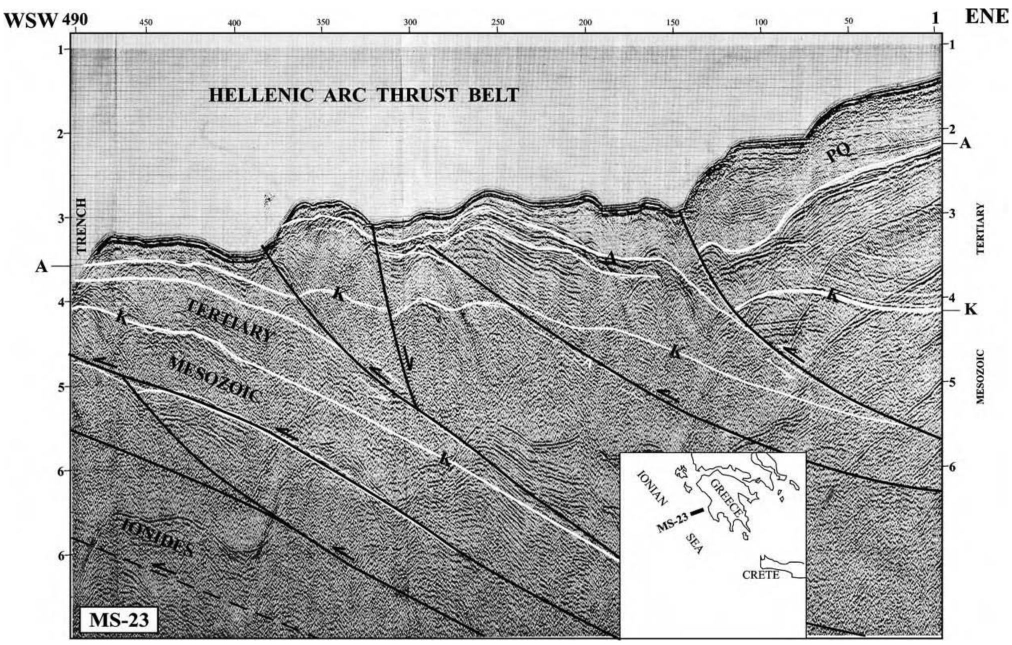


Fig. 2. 18 Example of MS seismic line across the Hellenic or Aegean Arc. There are evident imbricated thrust-blocks. The trench zone separates an internal orogenic sector (exhibited in this figure) formed by imbrication of continental thrust-blocks of the Hellenic arc, from an external sector (known in the literature as the "Mediterranean Ridge") mostly formed by repeated imbrication of Ionides which constitute a significant part of the wedge of the Hellenic and Calabrian arcs. (I.R. Finetti Crop project, Vol. 1 Deep seismic exploration of the central Mediterranean and Italy atlases in geoscience, 2006)

3. Literature review

3.1 Analytical approaches

The problem of pipelines crossing active faults has been approached using analytical, numerical, as well as experimental methods. The analytical solutions are reviewed herein.

Newmark and Hall (1975) were the first to study the problem of the effect of a fault movement on a pipeline. Their study focused on a pipeline subject to tensile strain induced by the rupture of a right lateral strike-slip fault intersecting the pipeline at an angle $\beta \leq 90^o$. In their model (Fig. 3. 1) the pipe is assumed to be firmly attached to the surrounding soil at two anchor points, which develop substantial resistance to the axial movement of the pipe. The bending stiffness of the pipe as well as the lateral pipe-soil interaction are neglected. The elongation of the pipe is considered to be composed of both an axial and a lateral component of the fault movement.

Because of symmetry, only one side of the fault trace is considered. The average pipe strain $\bar{\varepsilon}$, is:

$$\bar{\varepsilon} = \frac{\delta_f}{2L_a}\cos\beta + \frac{1}{2}\left(\frac{\delta_f}{2L_a}\sin\beta\right)^2$$

Where L_a is the effective unanchored length, that is, the distance between the fault trace and the anchor point. The first term accounts for the longitudinal component of the fault offset, that is, the average strain for a total displacement of $0.5\delta_f \cos\beta$ over a distance L_a. The second term accounts for arc-length effects and can be derived by applying the Pythagorean and Binomial Theorems.

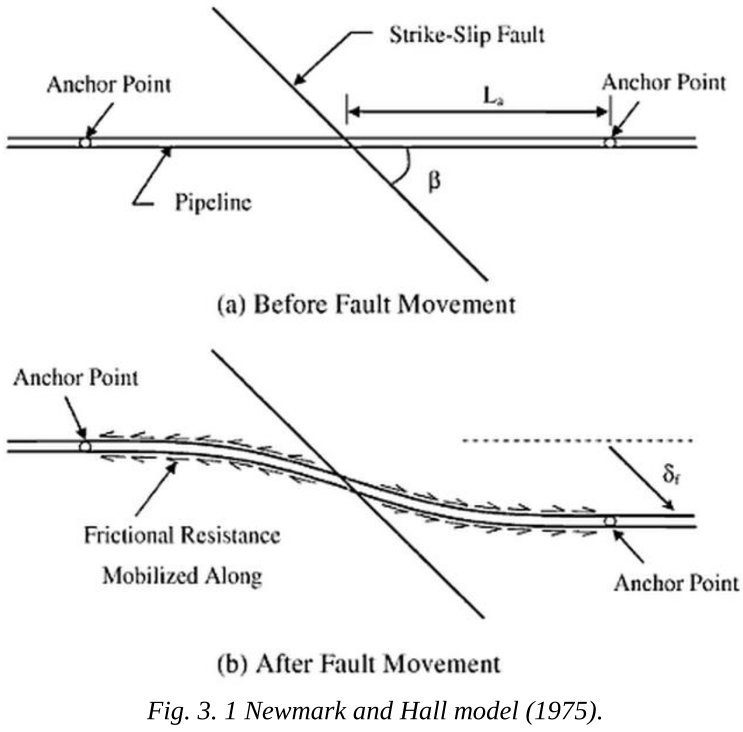


Fig. 3. 1 Newmark and Hall model (1975).

At the area near the fault, where there are no constraints, the only forces that cause the axial resistance of the pipeline are the friction forces. Failure in the Newmark and Hall approach is assumed to occur when the average strain exceeds the limit of 4%. Despite the fact that this approach provided insight on the mechanics of this problem, the tolerable fault movement for pipelines is overestimated, since the average strain is used as a failure criterion and the lateral interaction at the pipe-soil interface is neglected.

This model was further modified by Kennedy et al. (1977) by taking into account the soil-pipeline interaction in the transverse, incorporating the lateral pressure offered by the soil. They also considered the decrease of the pipe’s bending stiffness under the influence of large axial strains. It is assumed that the pipeline is a flexible cable deformed into a single constant curve approaching asymptotically to the undistorted portion of the pipeline. Unlike the Newmark-Hall model, bending and corresponding arc-length effects occur relatively close to the fault, while the axial friction forces extend well beyond the fault region. They focused on cases where the fault rupture provokes severe elongation of the pipeline, so as tension is the prevailing mode of deformation, and analyzed the relationship between the axial tensile force, the bending moment and the corresponding axial and bending strains.
The bending strain ε_b, is expressed as:

$\varepsilon_b = \dfrac{D}{2R_c}$, where R_c is the radius of curvature of the curved portion.

The total strain in the pipe is given by:

$\varepsilon = \varepsilon_a + \dfrac{D}{2R_c}$, where ε_a is the maximum axial strain due to the elongation of the pipe.

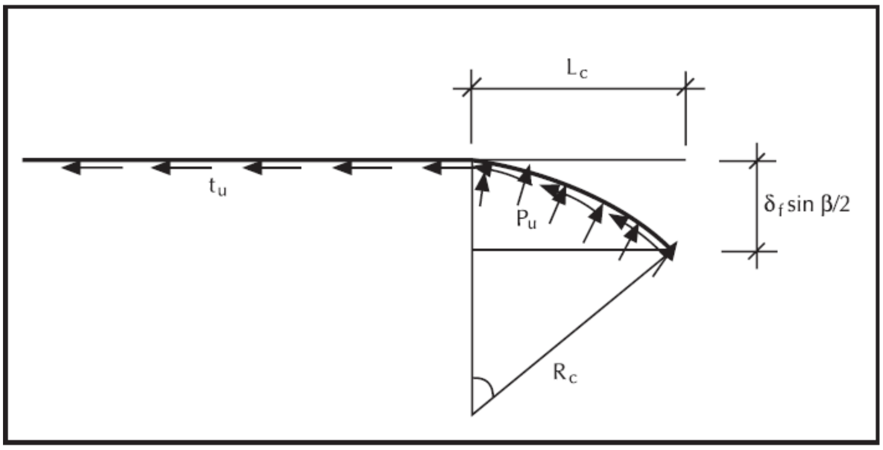


Fig. 3. 2 Kennedy et al. model (1977)

Subsequently, Wang and Yeh (1985) further modified this model by dividing the pipe into three regions depending on the curvature of the pipeline. More precisely, their model consists of a beam on an elastic foundation (BEF) that stands for the “straight” portion of the pipeline beyond the constant curvature region, and of the constant curvature region which is subdivided into elastic strain and inelastic strain regions. In their methodology, they neglect the influence of pipe axial stress on pipe bending stiffness and come with the conclusion that the pipe fails at the start of the BEF region.

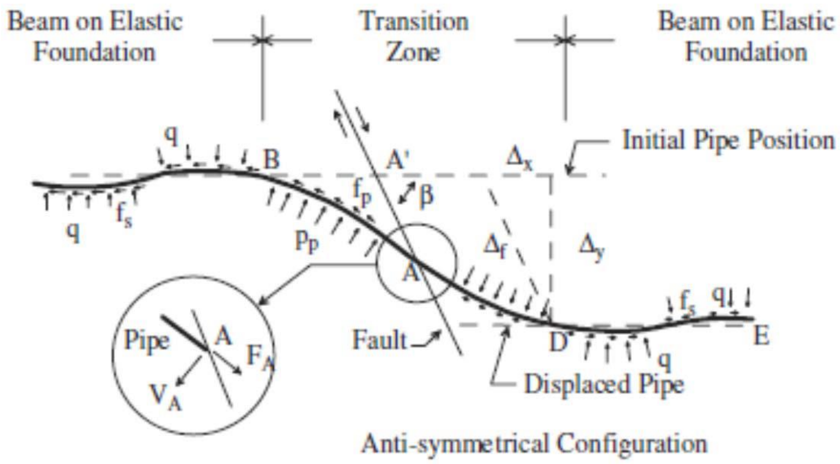


Fig. 3. 3 Pipeline analysis model proposed by Wang and Yeh (1985).

Karamitros et al. (2007) extended the Kennedy model and introduced number of refinements in the method proposed by Wang and Yeh (1985). Specifically, they adopted the pipeline segmentation proposed by Wang and Yeh, retained the beam on an elastic foundation for the “straight” portion of the pipeline, with the difference that the segments corresponding to the high-curvature zone of the pipeline were analyzed with the aid of the elastic-beam theory, in order to locate the most unfavorable combination of axial and bending strains. They also introduced material nonlinearity by assuming a bilinear stress-strain relationship for the pipeline steel. Their methodology is suitable for both small and large offsets but is strictly applicable to strike-slip faults, since a symmetric pipeline deformation about the intersection point of the pipeline axis with the fault trace is assumed. To account for situations with comparatively small offsets and low axial strain, they calculate the bending strain as follows:

$\frac{1}{\varepsilon_b} = \frac{1}{\varepsilon_b{}^{I}} + \frac{1}{\varepsilon_b{}^{II}}$, where $\varepsilon_b{}^{II}$ is the “curvature” bending strain and $\varepsilon_b{}^{I}$ is the strain due to the bending moment.

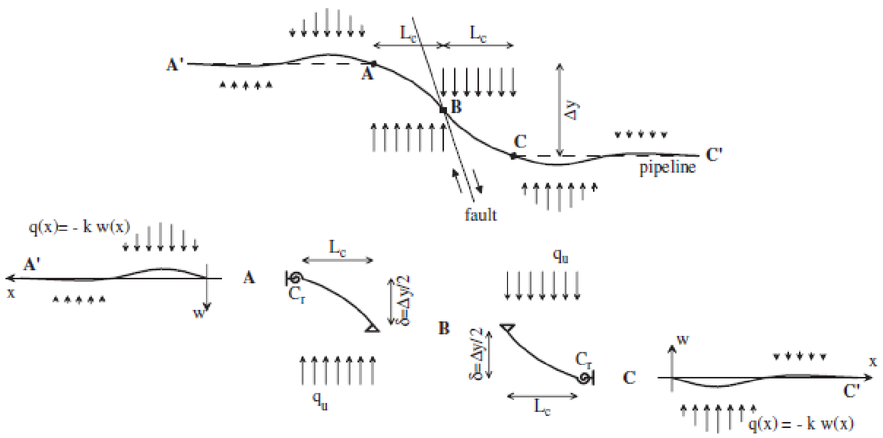


Fig. 3. 4 Partitioning of the pipeline into four segments. Wang and Yeh method on which Karamitros approach was based.

The model proposed by Karamitros et al. (2007) for strike-slip fault crossings was extended to normal fault crossings by Trifonov and Cherniy (2010). More specifically, they rejected the symmetry condition about the intersection point, proposed by Karamitros et al. (2007), allowing the analysis of different types of fault kinematics. In addition, within the four-segmented pipeline modelling, the two segments in high curvature zones on both sides of the fault were analyzed as beams under both bending and tension so that the axial force is directly included in the equations of motion. Finally, they took under consideration the contribution of transverse displacements in order to estimate more accurately the axial elongation of the pipeline. Although the model proposed by Trifonov and Cherniy, extended the field of application of the method to both strike-slip and normal faults, lacked of simplicity to their algorithms, causing complexity.

Subsequently, Karamitros et al. (2011) modified their initial model, introduced by Karamitros et al. (2007), extending their methodology to normal fault crossings, maintaining the simplicity of the equations used for the analysis. They examine the case of right (90^o) intersection angle between the pipeline axis and the fault trace and prove that the case of the intersection with an oblique fault can be decomposed into the separate problems of a strike-slip fault and a normal fault intersection, respectively. The intersection of the pipe with the fault trace is treated as a single point, as the fault is assumed to be an inclined plane without thickness of the rupture zone. The pipeline is discretized into three segments, the two of which are the straight segments of the pipeline away from the fault trace and are analyzed as beams on an elastic foundation. The drawback of this method is that the effects of local buckling are not taken under consideration and thus this method cannot be applied to cases where the strain extends beyond the strain limits defined by design codes.

The work of Trifonov and Cherniy (2010) has been extended by Trifonov and Cherniy (2011) in an attempt to refine the analytical model for inelastic material behavior of the steel pipeline. In their methodology, the plane stress conditions in the pipeline subjected to axial force, bending moment and internal pressure are treated systematically within the elasto-plastic framework.

3.2 Numerical approaches

An equally great number of researchers have studied this subject using numerical simulation and analysis. The case of a pipeline crossing a strike-slip fault has been studied by the majority of these researchers.

Takada et al. (2001) studied elasto-plastic shell-mode buckling of a pipe subjected to normal and reverse fault movement using shell finite element method. Based on analytical results and on Kennedy's work they proposed a simplified method for the maximum axial strain in steel pipes considering the deformation of the pipe cross-section. Kokavessis and Anagnostidis (2006), analyzed buried pipes under permanent ground-induced actions, using a finite element method and contact methods to describe pipe-soil interaction. Karamitros et al. (2007), in their analytical model, also presented a three-dimensional finite element model in order to compare the results with their analytical solutions, using nonlinear springs to simulate the soil behavior. Sihamoto et al. (2010) focused on the development of compressive strain limit of X80 pipelines to resist ground-induced actions. The seismic analysis of buried and unburied pipelines, under both transient and permanent ground movements have been examined by Arifin et al. (2010), using beam finite elements for the pipeline and nonlinear springs to model the effects of the surrounding soil. Odina and Tan (2009) investigated buried pipeline response under seismic fault displacement, using a beam-type finite element model with elastic-plastic springs for the soil effects. In a subsequent publication, Odina and Conder (2010), extended the work by examining the effects of Lüder's plateau of the stress-strain material curve on the pipeline response crossing active faults. Gu and Zhang (2009), have presented a similar methodology for pipelines crossing faults, based on beam-elemnt simulation of the buried pipeline and using nonlinear springs for the surrounding soil, aiming at determining the optimum crossing angle for the pipeline. Vazouras et al. (2010) investigated the mechanical behavior of buried steel pipelines, crossing an active strike-slip tectonic fault using a finite elements model, which account for large strains and displacements, nonlinear material behavior and special conditions of contact and friction on the soil–pipe interface. Their study focused on the effects of various soil and pipeline parameters on the structural response of the pipe as well as the influence of internal pressure on the structural response. In a subsequent publication, Vazouras et al. (2012) extended their investigation based on a numerical simulation of the nonlinear response of the soil– pipeline system through finite elements, accounting for large strains and displacements, inelastic material behavior of the pipeline and the surrounding soil, as well as contact and friction on the soil– pipe interface.

3.3 Experimental work

In addition to all the above studies, notable experimental works have been reported in series of recent papers by Ha et al. and Abdoun et al., investigating the effects of strike slip faults on buried high-density polyethylene (HDPE) pipelines. This experimental project was based on centrifuge modeling of pipeline response to seismic faulting, examining the influence of the type of faulting, the angle of strike-slip faults on the pipeline mechanical behavior, as well as the effects of buried depth and pipeline diameter and moisture content.

Finally, Sim et al. (2011) (Imperial College of London and University of Tokyo) performed a series of shaking table tests modeling small diameter pipes crossing a vertical fault. Their results indicated that the magnitude of bending moment is directly affected by the magnitude of fault displacement irrespective of any other factors. In particular, the intensity of shaking does not play a significant role in the magnitude of bending moment caused by fault action. In their experiments they also used tyre derived aggregate (TDA) backfill and proved that it is capable of reducing the bending moments incurred due to simultaneous faulting and shaking for maximum accelerations less than or equal to 0.5 g and vertical fault displacements less than the pipe diameter by up to 74%.

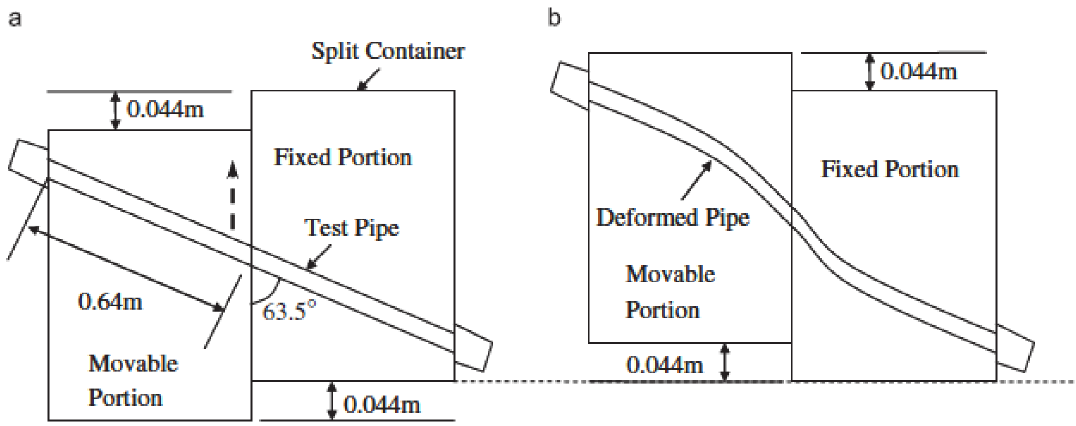


Fig. 3. 5 Plan view of the centrifuge model before and after offset (dimensions in model scale) used by Abdoun et al. (2009)

3.4 Guidelines regarding pipeline fault crossings

After an extensive literature review of the provisions of the seismic norms worldwide, it has been observed that there is a lack of sufficient guidelines regarding offshore pipelines crossing active seismic faults.

In particular, concerning *offshore* pipelines, ISO 19901 "Petroleum and natural gas industries-Specific requirements for offshore structures, Part 2- Seismic design procedures and criteria" as well as the standard of American Petroleum Institute "Design, Construction, Operation and Maintenance of Offshore Hydrocarbon Pipelines", do not include specific guidelines or any design provisions for offshore pipelines crossings active faults, except the fact that fault crossings should be avoided. In the offshore standard DNV "Submarine pipeline systems" is mentioned that in areas where there is evidence of increased geological activity or significant historic events that may impact the integrity of the pipeline, additional geo-hazard studies should be performed.

On the contrary, there are plenty of guidelines and design provisions concerning *onshore* buried pipelines crossing active faults, such as EC8, IITK-GSDMA and ALA. According to modern norms, the evaluation of pipeline response to faulting requires numerical analyses that account for non-linear soil and pipeline behavior. The provisions of the norms concerning *onshore pipelines* crossing active seismic faults are presented in more detail in Appendix A for easy reference.

4. Numerical modelling

In the present chapter, an investigation of the mechanical properties of offshore steel pipes crossing active seismic faults is being performed. As the fault is displaced, pipes are subject to axial, shear and bending forces and they develop stresses as well as inelastic strains. High tensional strains may cause to cracks’ creation on the welding areas while high compression strains may cause to local buckling to the side walls of the whole pipeline.

In order to examine the most influencing factors to the distress of pipelines subjected to fault rupture(s), a numerical parametric study was conducted using the commercial finite element analysis code ABAQUS. This parametric study was performed after the validation of the numerical model with the mechanical and geometrical properties of the pipeline that had been examined in Karamitros et al.

4.1 Description of the finite element model

The model that was considered is a typical offshore high-pressure natural gas pipeline with an external diameter of 0.9144 m (36 in) and a wall thickness of 0.027 m (1.063 in). The total length of the model is 1000 m and the pipe intersects a fault in the middle of its length at 90°. The pipe is discretized into 1000 equal size pipe elements, each of 1.0 m length.

The pipeline model is made of steel API-X65 type, with a bilinear elasto-plastic stress-strain behavior, as presented in Fig. 4. 1, with the properties of the material listed in Table II.

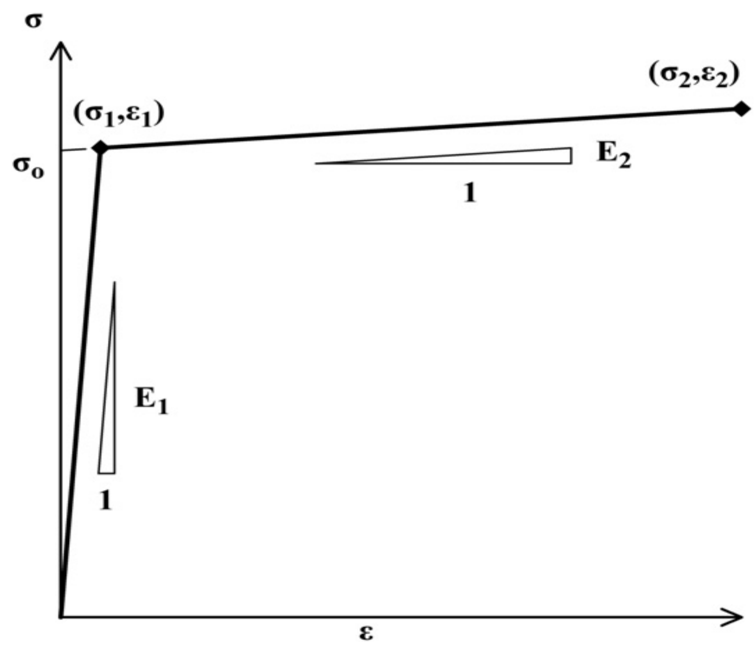


Fig. 4. 1 Bilinear stress-strain relationship assumed for the pipeline steel

TABLE II
API5L-X65 STEEL PROPERTIES

Yield stress (σ_1)	490 MPa
Failure stress (σ_2)	531 MPa
Yield strain (ε_1)	0.233 %
Failure strain (ε_2)	4 %
Elastic Young's modulus (E_1)	210 GPa
Plastic Young's modulus (E_2)	1.088 GPa

In order to simulate the pipe-soil interaction, each node of the designed pipeline was connected with soil springs in the axial, the transverse horizontal and the transverse vertical direction (Fig. 4. 2). The properties of the aforementioned springs used for the analyses are listed in Table III. The fault displacement was applied to the pipeline statically, by displacing the free ends of the corresponding soil springs.

Note that for constructability issues offshore pipelines are mainly located above seabed, while at the landfall areas offshore pipelines may be buried along a certain extent. It is evident that in the case of an above-seabed pipeline, some of the aforementioned soil springs may be neglected depending on the circumstances.

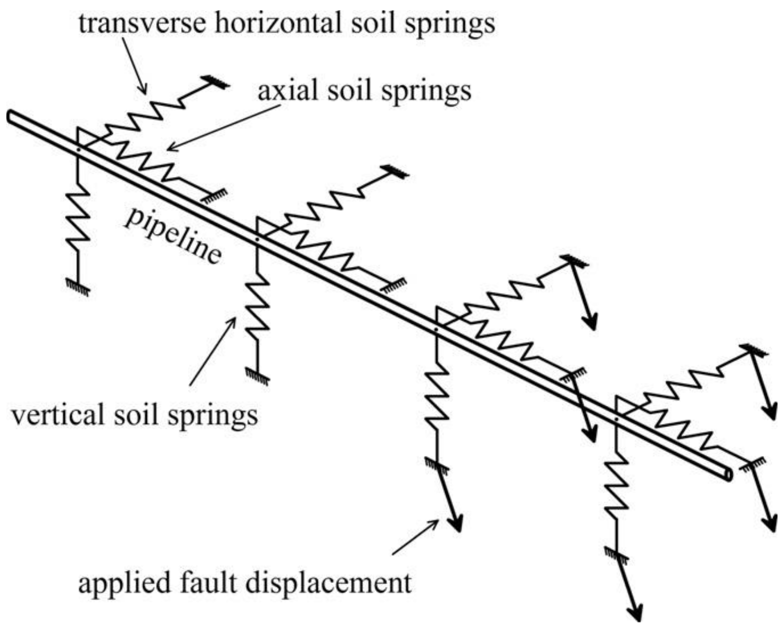


Fig. 4. 2 Schematic presentation of the 3D model used to conduct the finite element analysis

TABLE III
SOIL SPRING PROPERTIES

Spring type	**Yield force (kN/m)**	**Yield displacement (mm)**
Axial (friction)	40.5	3.0
Transverse horizontal	318.6	11.4
Vertical (upward displacement)	52.0	2.2
Vertical (downward displacement)	1360.0	100.0

Finite Element Analysis program "Abaqus" is considered one of the most trustworthy means of modelling pipelines crossing faults. In Abaqus there is a great library of finite elements available in order to model a pipe, e.g. beam elements, pipe elements and shell elements. The pipeline in the present study was modelled with pipe 3-D elements. Some typical examples of the model in Abaqus are presented below.

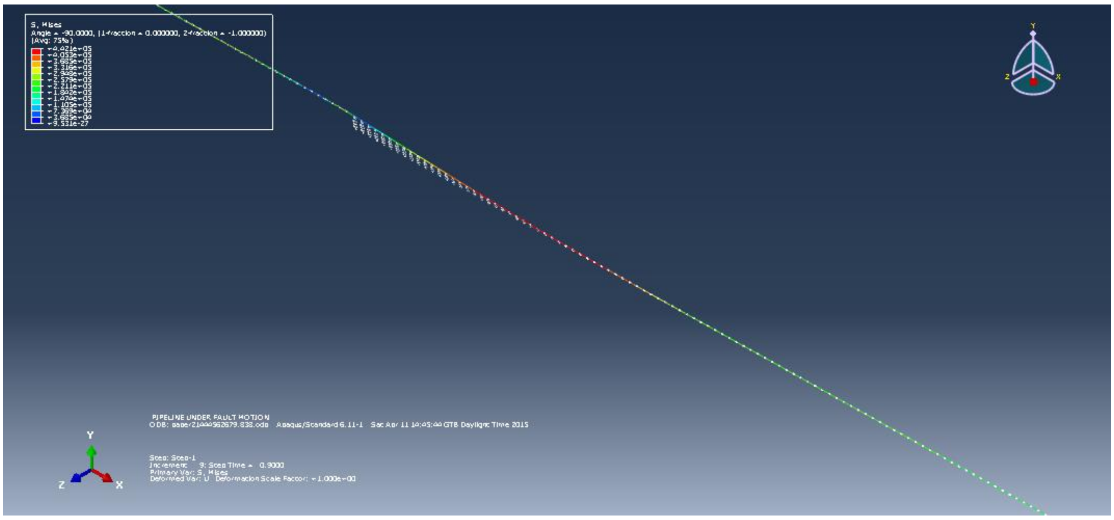


Fig. 4. 3 Plot contours on deformed shape in Abaqus – Von Mises stresses, Normal fault

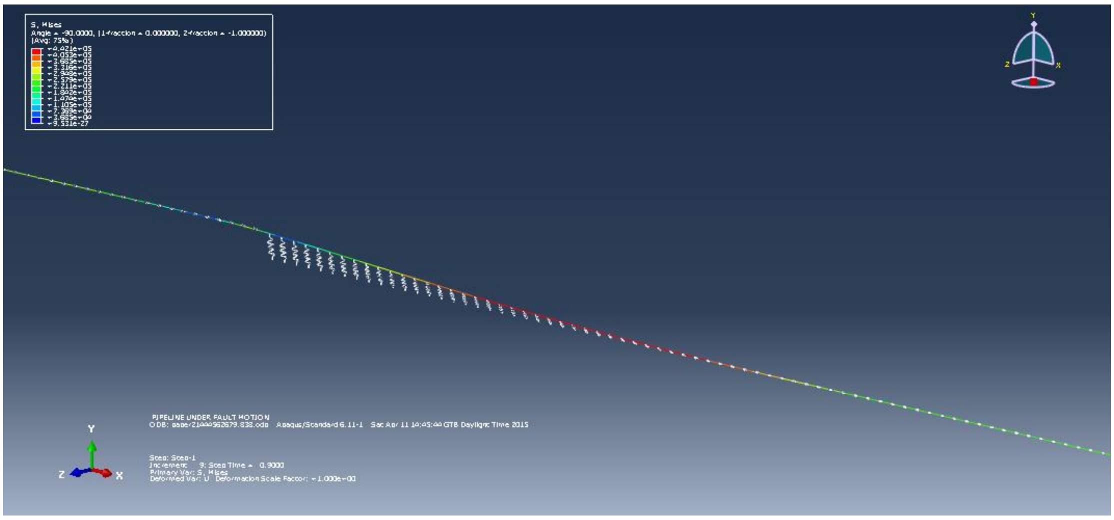


Fig. 4. 4 Plot contours on deformed shape in Abaqus – Von Mises stresses, Normal fault

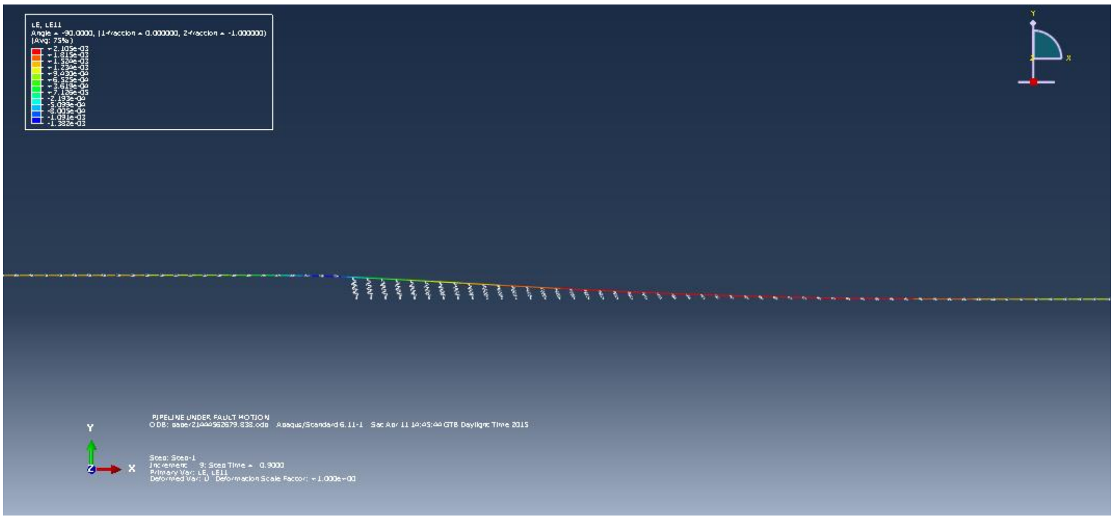


Fig. 4. 5 Plot contours on deformed shape in Abaqus – Axial strains, Normal fault

4.2 Validation of the numerical method

As mentioned before, a validation of the numerical simulation is being performed, comparing the numerical results with the relevant analytical solutions based on the analytical method of Karamitros et al. (2011). The model used for the validation had to keep equal geometrical properties as the analytical model used in Karamitros et al. study. The dimensions of the validation model are listed below:

- The external diameter of the pipeline is 0.9144m, same as the diameter of the pipeline examined in the rest of the parametric study.
- The wall thickness is 0.0119m instead of 0.027m.
- The steel properties and the properties of the surrounding soil are identical with the ones described in the previous section (i.e. section 4.1).

A range of analyses were conducted, for three different angles of the fault plane $\psi=55^o$, 70^o, 85^o. In each case, the fault displacement ranges from 0.1D to 2.0D, applied incrementally with a step size of 0.1D. The results of the comparison are presented in Fig. 4. 6.

The comparison shown in Fig. 4. 6, is made over the peak values of axial strain ε_a, bending strain ε_b and total strain $\varepsilon_{max}= \varepsilon_a+ \varepsilon_b$. A good agreement may be testified for all components of pipeline strain in the two first cases ($\psi=55^o$, 70^o). In the case of the nearly vertical fault plane ($\psi=85^o$) there is a good agreement with the analytical solutions for fault displacements up to 1.6D, while for greater fault displacements there is an obvious difference between the numerical and analytical results to all strains. In the aforementioned case, strains present an abrupt increase for fault displacements greater than 1.6D, although such a fault angle is rather unusual in practice. Note that similar discrepancies between analytical and numerical results had been observed by Karamitros et al. as well. This difference is attributed to a simplifying assumption that was made in the analytical model of Karamitros, that according to his study is realistic for small pipeline strains and inclined fault planes, but becomes unrealistic as yielding extends over a major portion of the pipeline cross section, creating essentially a plastic hinge at the intersection with the fault trace, while the fault plane tends also to become vertical.

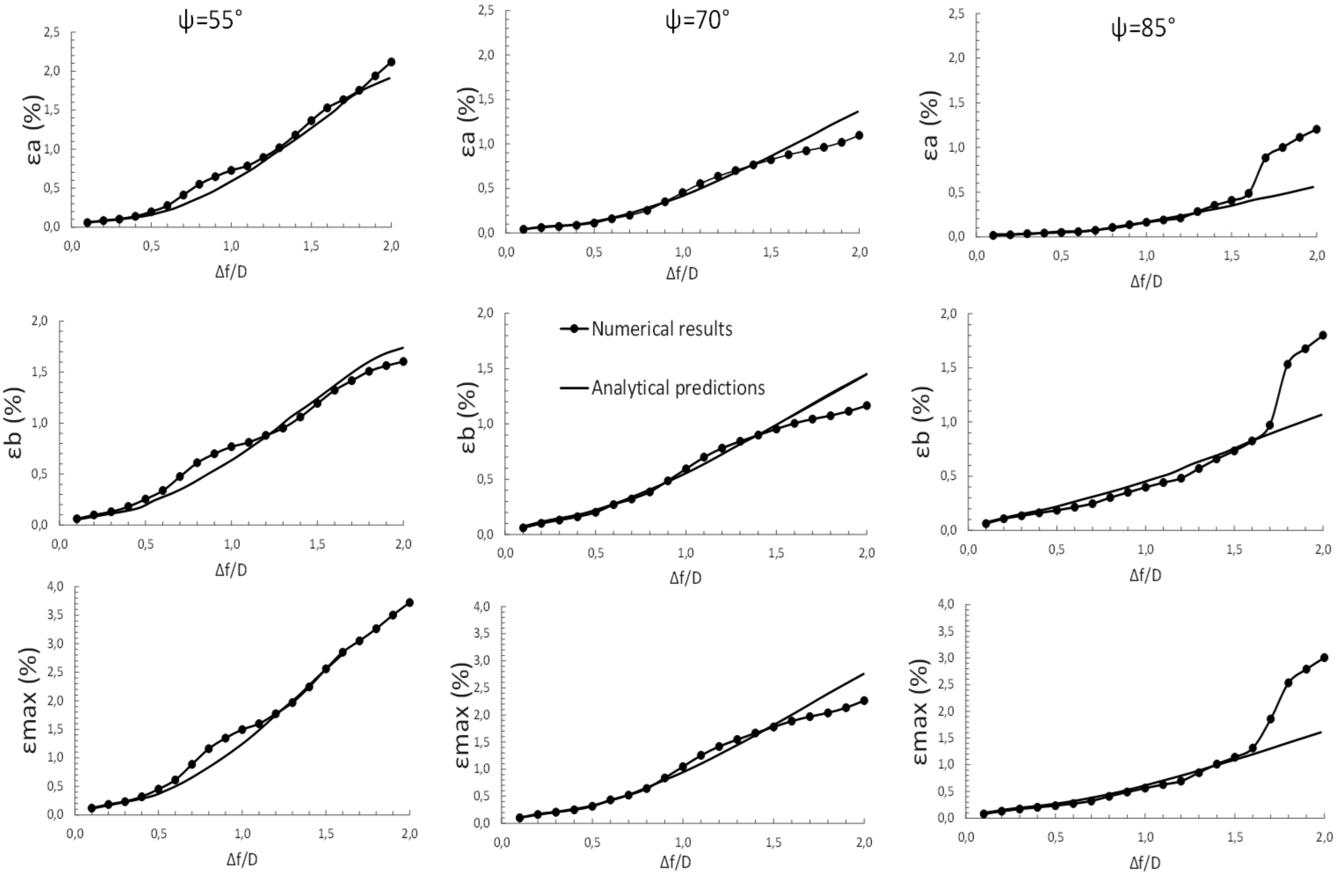
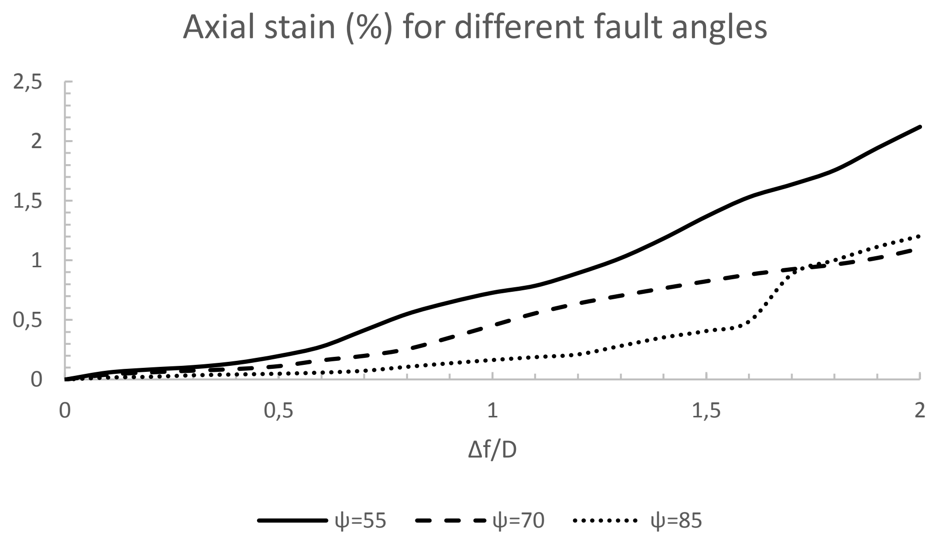
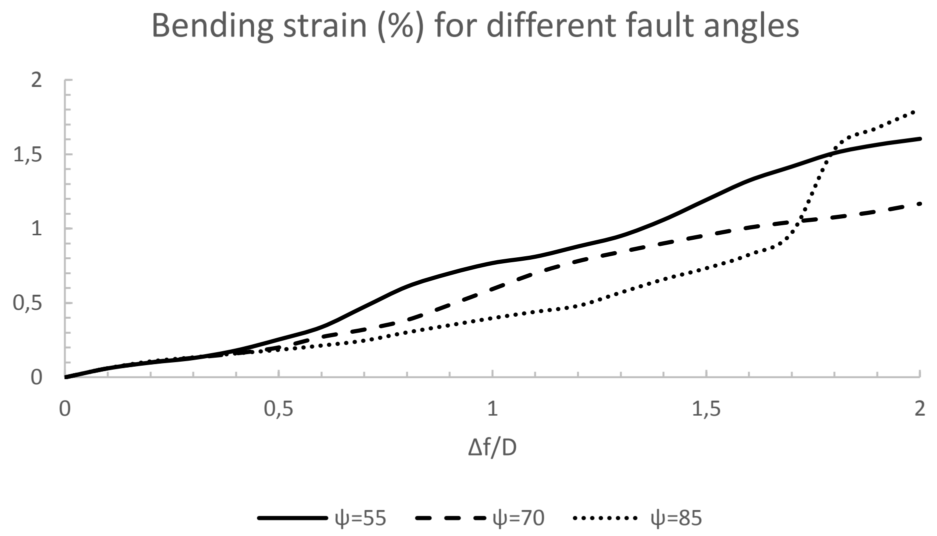


Fig. 4. 6 Numerical results of the current study versus the analytical predictions from Karamitros et al. Peak values of axial strain ε_a, bending strain ε_b and total strain $\varepsilon_{max}= \varepsilon_a+ \varepsilon_b$ as a function of the ratio Δf/D for fault angles ψ=55°, 70°, 85°.

Other conclusions may also rise from Fig. 4. 6 comparing the results for different fault plane angles summarized in Fig. 4. 7. The greater values of strain appear in the case of the smaller fault angle (ψ=55°) where for a maximum displacement of 2.0D the axial strain reaches 2% against 1.1% in the case of ψ=70° and 1.2% in the case of ψ=85°, respectively. Such a difference is also obvious in the case of maximum strains, where it is observed that values of axial strain for a fault angle of ψ=55° are greater than the corresponding cases of ψ=70° and ψ=85° respectively (i.e. ~4.0% over 2.0% and 3.0% respectively). On the other hand, bending strains tend to keep a greater value in cases for Δf/D smaller than 1.7, but in the case of the nearly vertical fault plane (ψ=85°) for fault displacements greater than 1.6D bending strains reach bigger values.





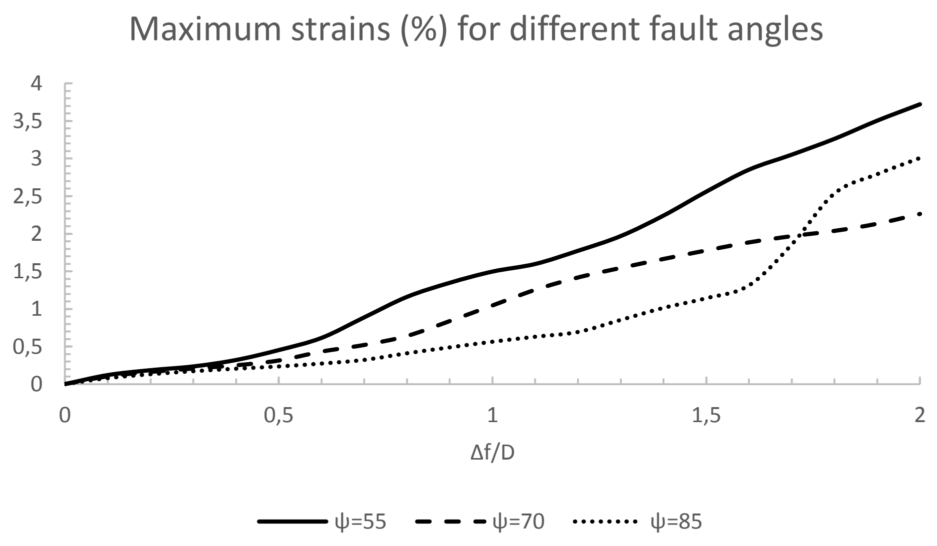


Fig. 4. 7 Variation of peak values of axial strain ε_a, bending strain ε_b and total strain $\varepsilon_{max}= \varepsilon_a+ \varepsilon_b$ as a function of the ratio $\Delta f/D$ and the fault plane angles ψ=55°, 70°, 85°.

4.3 Parametric study

A parametric study was conducted in order to examine the most influencing factors to the distress of pipelines subjected to fault rupture(s) and to obtain the pipeline response under various conditions.

The parameters examined in order to obtain the pipeline response under various conditions are:

- The fault offset (normal or reverse fault)
- The hydrostatic (external) pressure
- The soil conditions
- The wall thickness of the pipe

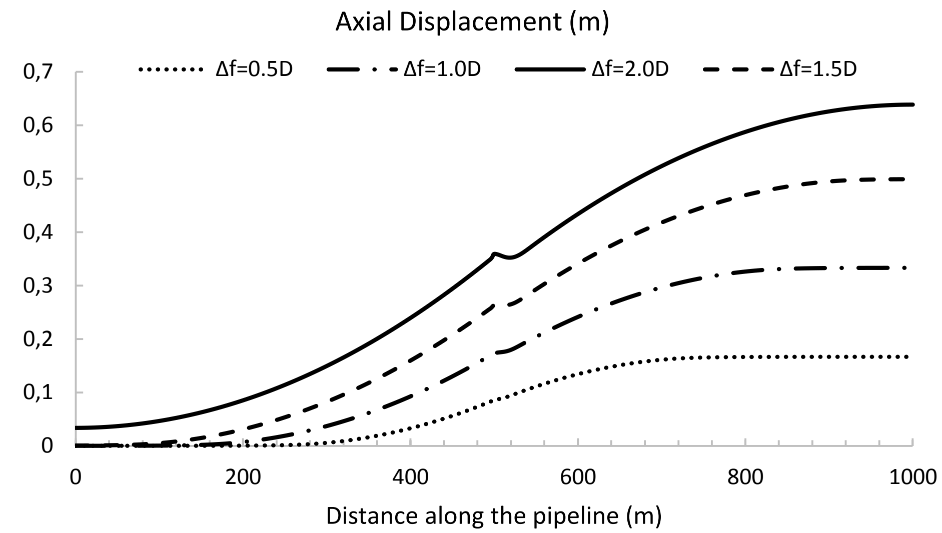
The angle of the fault that was considered for all types of the analyses is $\psi=70^o$ relative to the horizontal plane. In each case the most influencing factors to the pipeline's distress are calculated and presented in the form of diagrams as a function of pipe's length, including axial and vertical displacement, axial and shear forces, bending moment, soil friction, soil resistance and axial and bending strains.

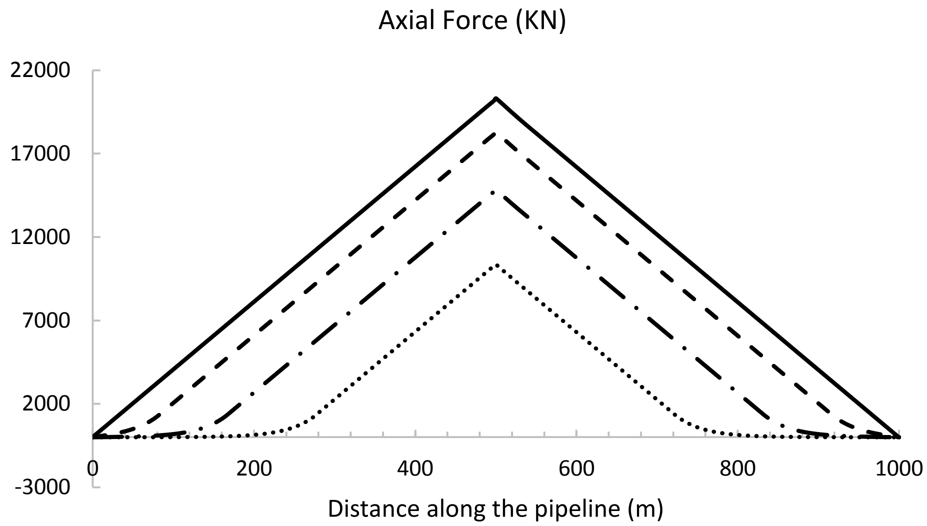
4.3.1 The fault offset (normal and reverse fault)

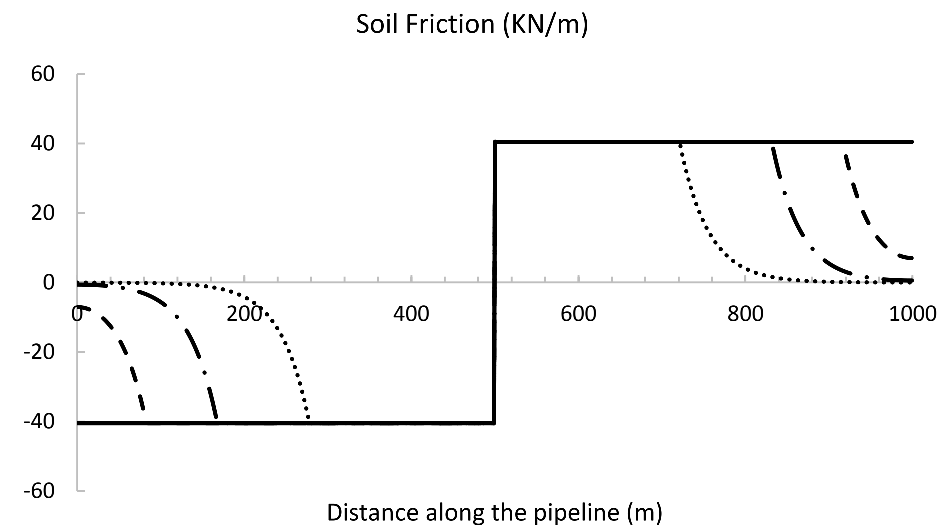
First of all the impact of the fault offset was examined at an intersection with a normal fault. The angle of the fault was considered as $\psi=70^o$ relative to the horizontal plane. The fault displacements considered were Δf = 0.5D, 1.0D, 1.5D, 2.0D, with D being the external diameter of the pipe.

Fig. 4. 8 presents the axial displacement, the axial force and the axial strain of the pipe, as well as the soil friction forces, along the length of the pipeline for the considered fault displacements. The axial displacement of the pipe is distributed over a large component of the pipeline, depending on the size of the fault offset, hereafter denoted "unanchored length". As it was expected, for larger fault offsets, the unanchored length is larger, presenting greater displacement values. The pipeline elongation within this length results in the development of axial tensile forces. As shown in the relevant diagram, axial tensile forces present a maximum value at the intersection point of the pipeline with the trace of the fault and decrease linearly away from the fault due to the friction forces developed. Soil friction forces obtain their limits along the whole unanchored length. The peak value of the soil friction force reaches 40 kN for all the considered fault displacements.

The axial strains also present a linear behavior with a significantly larger peak value at the intersection point of the pipeline with the fault trace, decreasing linearly with the distance away from this point. The maximum axial strain for a fault offset Δf=2.0D reaches 0.36%, substantially greater than the axial strain for a fault offset Δf=1.5D which reaches almost 0.20%. It becomes evident that the axial strains may overcome the yield strain of the pipe's material (0.233 %) and as a result the pipeline will have inelastic deformations that may cause serious damage to many of the pipe's components. In all cases the axial strain does not reach the failure strain (4%) which would cause the total damage of the whole pipeline.


Axial Displacement (m)
Δf=0.5D
Δf=1.0D
Δf=2.0D
Δf=1.5D
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
200
400
600
800
1000
Distance along the pipeline (m)


Axial Force (KN)
22000
17000
12000
7000
2000
-3000
0
200
400
600
800
1000
Distance along the pipeline (m)


Soil Friction (KN/m)
60
40
20
0
-20
-40
-60
0
200
400
600
800
1000
Distance along the pipeline (m)

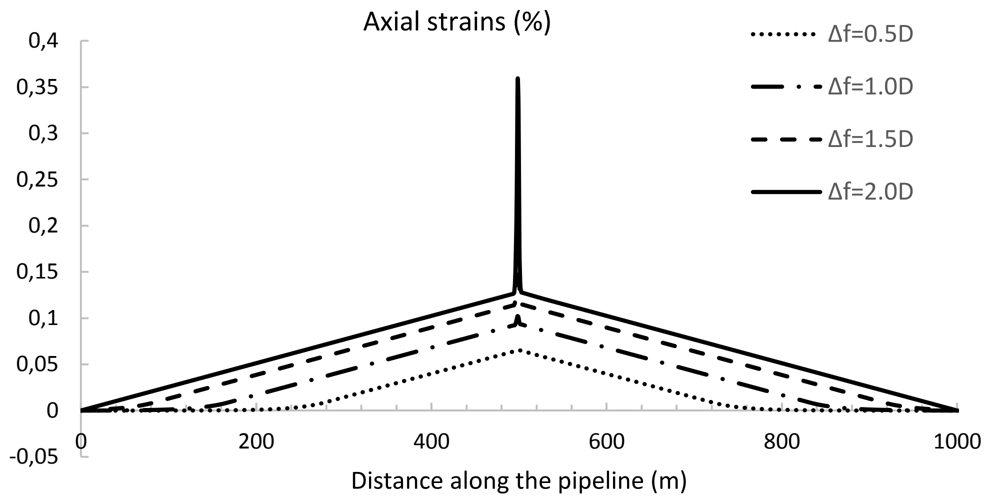
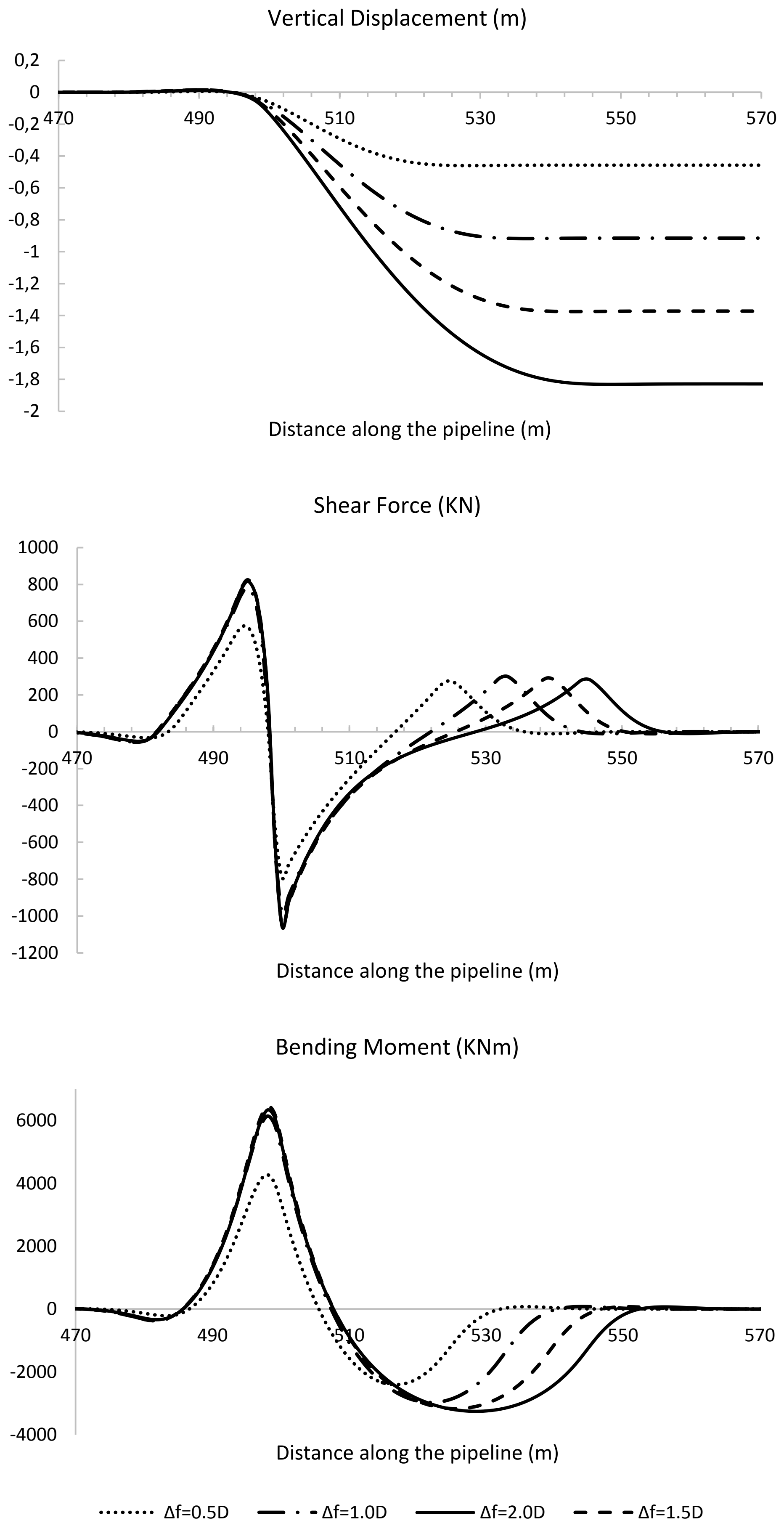
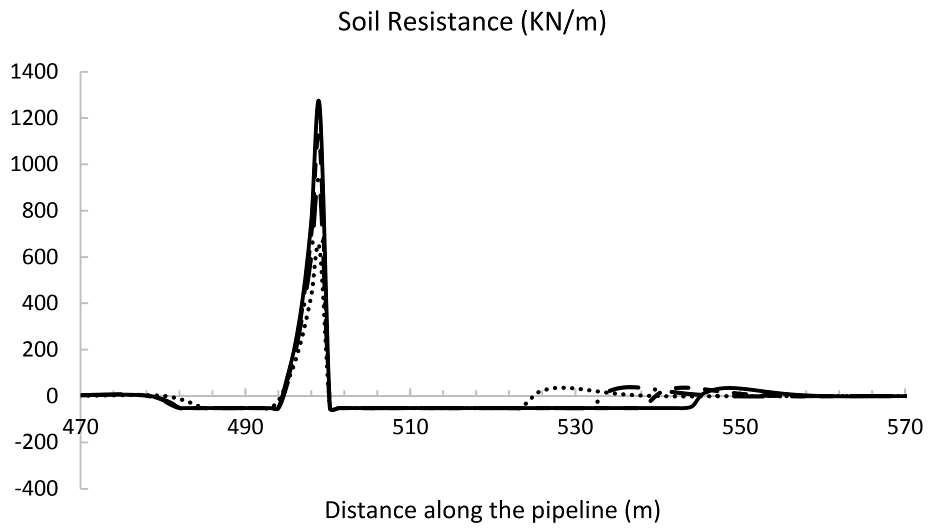


Fig. 4. 8 Axial displacement, axial force, soil friction forces and axial strain along the length of the pipeline for the considered fault displacements; intersection with a normal fault

Fig. 4. 9 shows the vertical displacements, shear forces, bending moments, bending strains and spring forces for upward and downward pipeline displacement corresponding to the soil resistance, focusing on the central area of the pipeline near the fault trace. The length of the pipeline subjected to vertical displacement hereafter denoted "curved length", appears to be considerably smaller than the corresponding length subjected to axial displacement (i.e. unanchored length). Vertical displacement is not evenly divided on both sides; it occurs mainly over the hanging wall of the fault, being 3-4 times longer than the segment over the foot wall. This is attributed to the resistance forces of the soil, which present significantly larger values on the footwall of the fault and as a result the segment of the pipeline on the hanging wall of the fault accommodates most of the vertical component of the fault movement.

Concerning the shear forces and bending moments, they present similar peak values, despite the variation of the fault offset, except of the smallest fault displacement. In the case of small ground displacement (Δf=0.5D), the distribution along the pipeline is similar to that of an elastic beam, with a triangularly distributed upward load, a uniformly distributed downward load and a downward applied displacement which is equal to the vertical component of the applied fault displacement.


Vertical Displacement (m)
0,2
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
-1,8
-2
470
490
510
530
550
570
Distance along the pipeline (m)
Shear Force (KN)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
470
490
510
530
550
570
Distance along the pipeline (m)
Bending Moment (KNm)
6000
4000
2000
0
-2000
-4000
470
490
510
530
550
570
Distance along the pipeline (m)
Δf=0.5D
Δf=1.0D
Δf=2.0D
Δf=1.5D



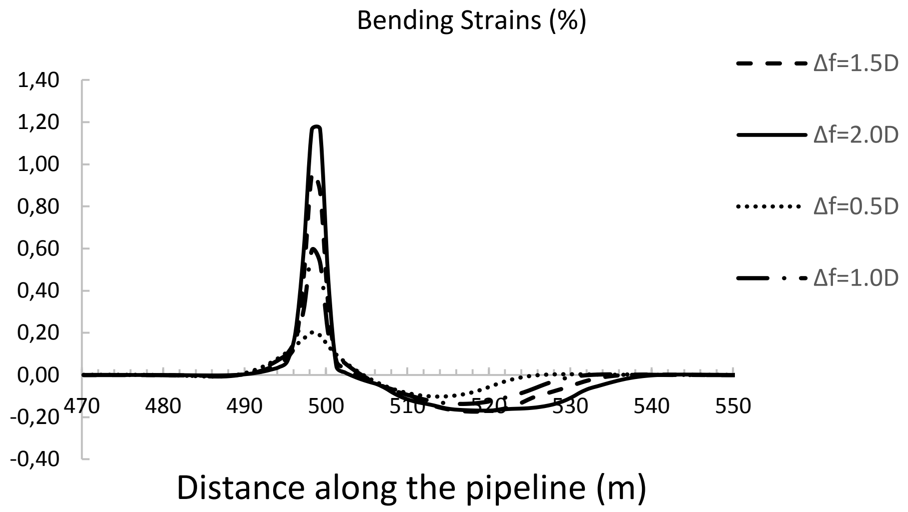
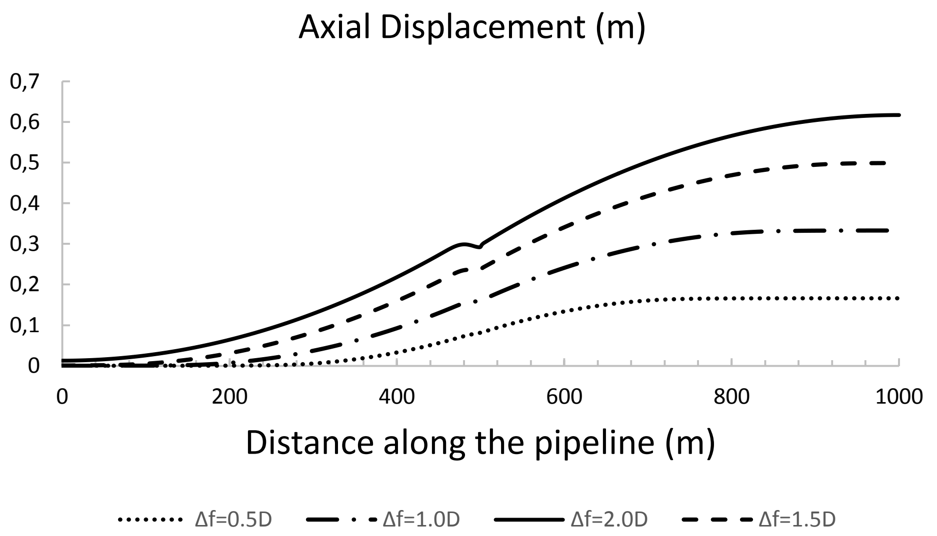
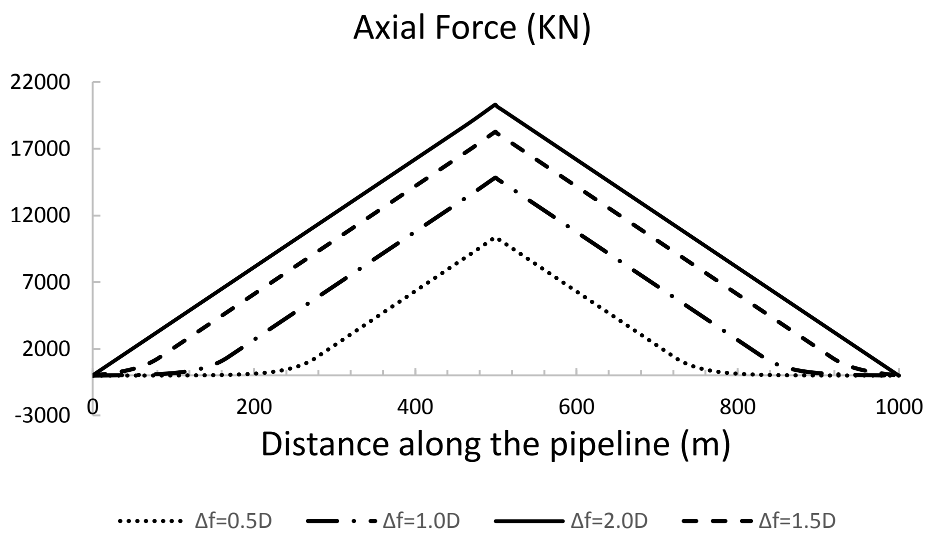
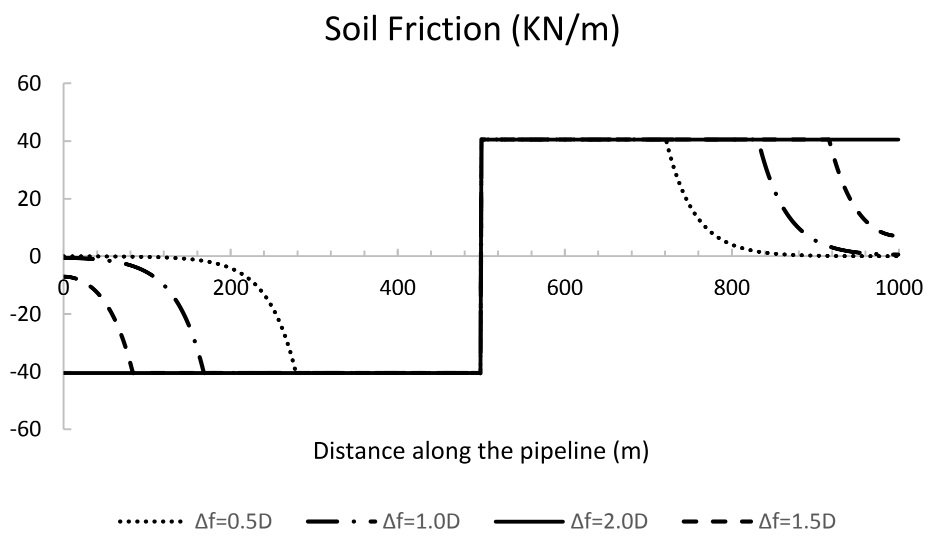


Fig. 4. 9 Vertical displacements, shear forces, bending moments, soil resistance forces for upward and downward displacement and bending strains along the length of the pipeline, in the area near the fault trace; intersection with a normal fault

Subsequently, the same model of the pipeline was analyzed in an intersection with a reverse fault with characteristics identical to the characteristics of the previously examined normal fault (Fig. 4. 10 and Fig. 4. 11). In the case of the intersection with a reverse fault, the pipeline is subjected to axial tensile forces of the same order as in the case of the normal fault reaching a maximum axial strain of 0.35% for a fault displacement of 2.0D. The most significant difference between the cases of the normal and reverse fault is the value of bending strain, as in the case of the reverse fault, bending strains present smaller peak values for all fault offsets than the corresponding strains of the normal fault case. More precisely, the peak value of the bending strain for a fault offset of 2.0D is 1.2% for the intersection with a normal fault, while it is 0.5% in the case of intersection with a reverse fault.


Axial Displacement (m)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
200
400
600
800
1000
Distance along the pipeline (m)
Δf=0.5D
Δf=1.0D
Δf=2.0D
Δf=1.5D


Axial Force (KN)
22000
17000
12000
7000
2000
-3000
0
200
400
600
800
1000
Distance along the pipeline (m)
Δf=0.5D
Δf=1.0D
Δf=2.0D
Δf=1.5D


Soil Friction (KN/m)
60
40
20
0
-20
-40
-60
0
200
400
600
800
1000
Distance along the pipeline (m)
Δf=0.5D
Δf=1.0D
Δf=2.0D
Δf=1.5D

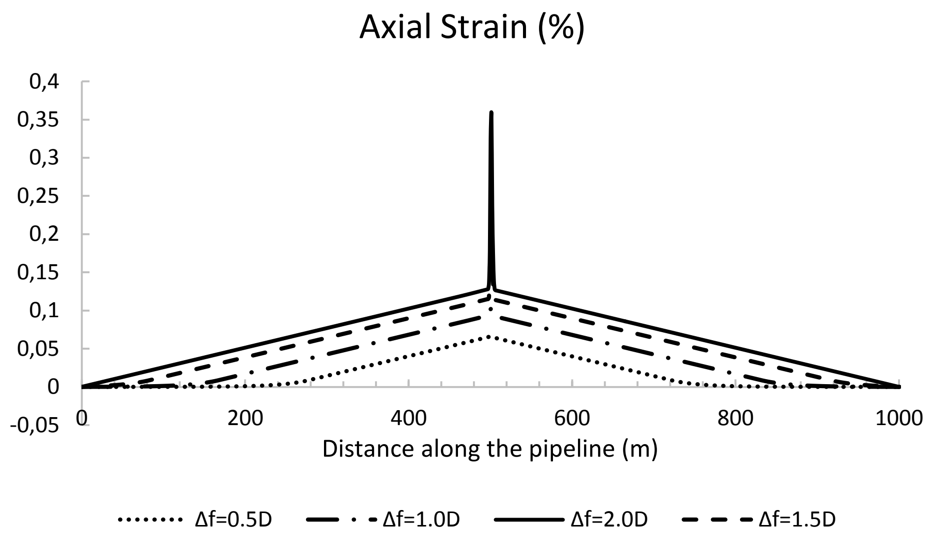
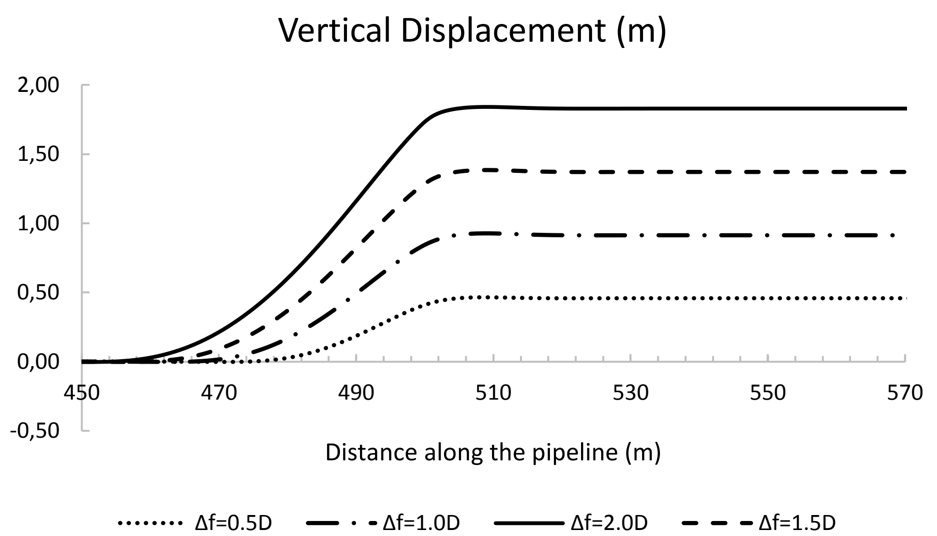
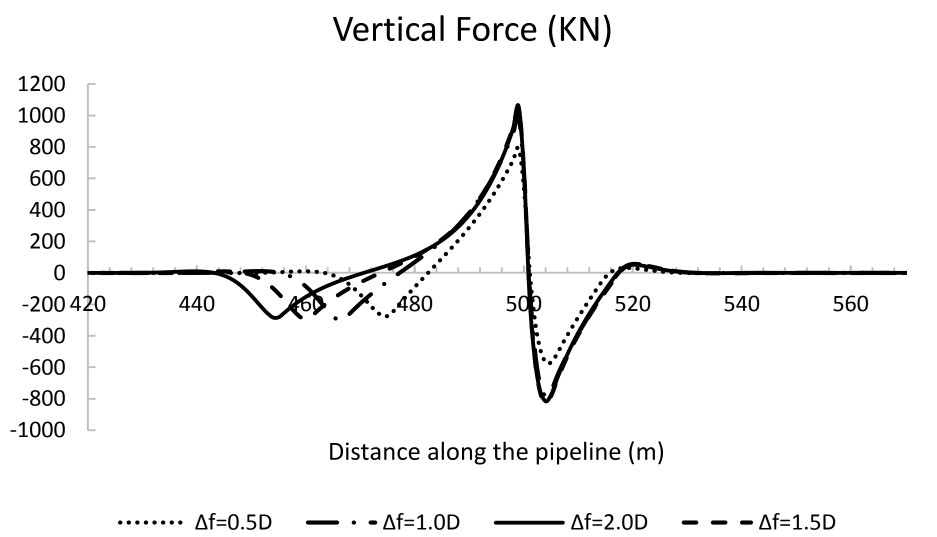
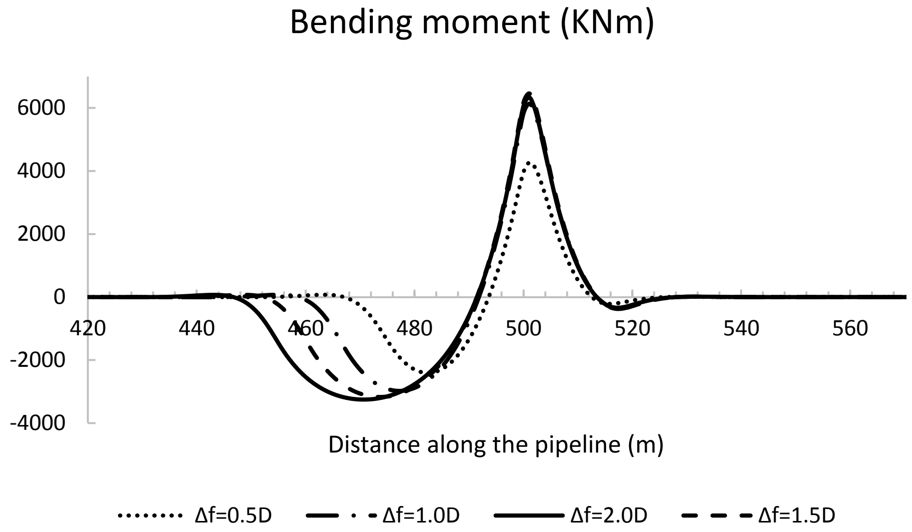
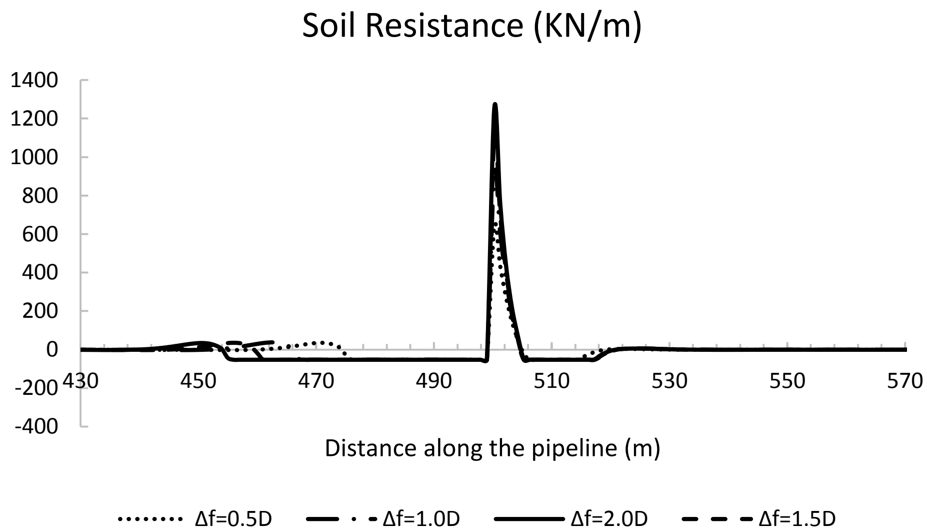


Fig. 4. 10 Axial displacement, axial force, soil friction forces and axial strain along the length of the pipeline for the considered fault displacements; intersection with a reverse fault









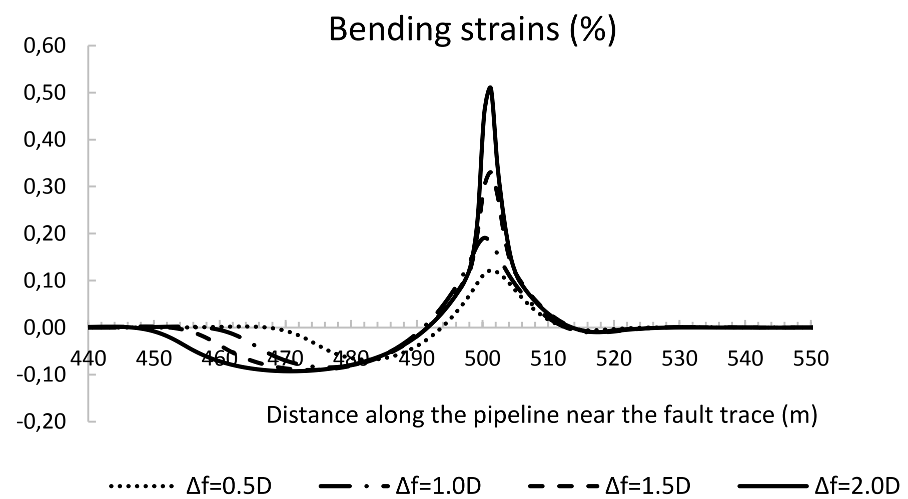


Fig. 4. 11 Vertical displacements, shear forces, bending moments, soil resistance forces for upward and downward displacement and bending strains along the length of the pipeline, in the area near the fault trace; intersection with a normal fault

4.3.2 The pressure state of the pipeline

Another parameter examined, is the impact of the internal pressure of the pipeline, due to the gas transmitted through the pipe, as well as the impact of the external pressure when the pipeline is underwater, depending on the depth of the establishment. The assumed pressures used for the analyses are presented in Table IV and the results in Fig. 4. 12 - Fig. 4. 15. All the cases were studied under a fault rupture of offset Δf=2.0D of a normal fault.

TABLE IV
PRESSURE STATES ASSUMED FOR THE ANALYSES

Pressure state	$P_{internal}$ (kPa)	$P_{external}$ (kPa)
1. Zero pressure	-	-
2. Internal pressure	11,000	-
3. Depth 500 m	11,000	4,904
4. Depth 1000 m	11,000	9,807
5. Depth 2000 m	11,000	19,614

The variation of axial displacements, axial forces, soil friction forces and axial strains along the length of the pipeline are presented in Fig. 4. 12 and Fig. 4. 13. The more unfavorable state of pressure for the pipeline is the case of internal pressure and external hydrostatic pressure in a depth of 500m. In the aforementioned case, the "unanchored length" of the pipeline is now the whole length of the pipeline as axial forces extend to the whole length of the pipeline, causing axial strains that reach up to 0.35%. In addition, almost as high strains are reached in the case of no pressures. The increase of the water depth results to a decrease in the axial forces, subjecting the pipe to compression for a great depth of 2000 m. The allocation of the diagrams of axial force and soil friction present a difference in the case of the pipeline where only internal pressures exist.

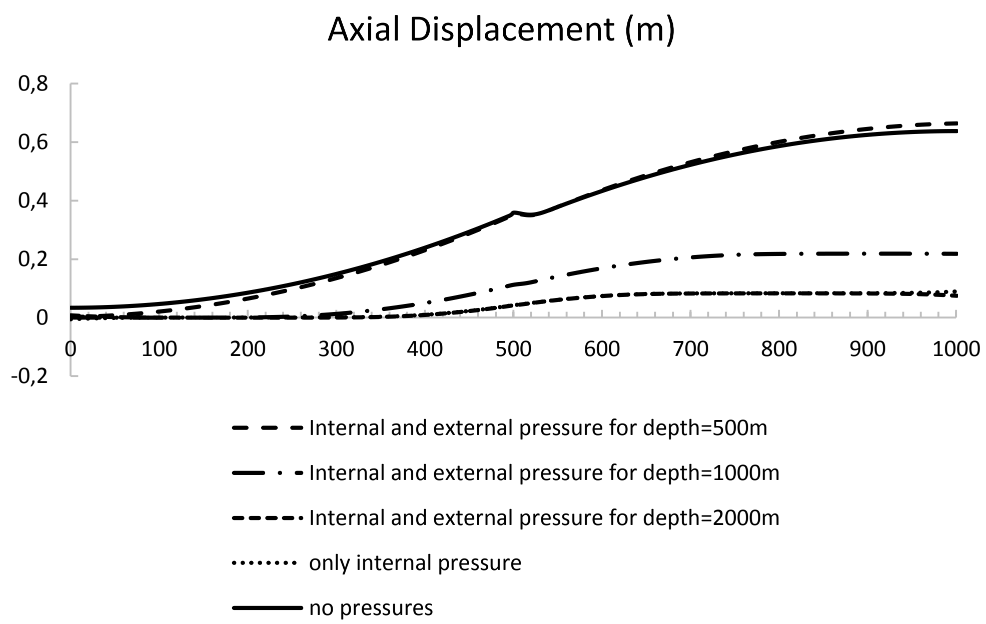


Fig. 4. 12 Axial Displacement along the length of the pipeline; intersection with a normal fault

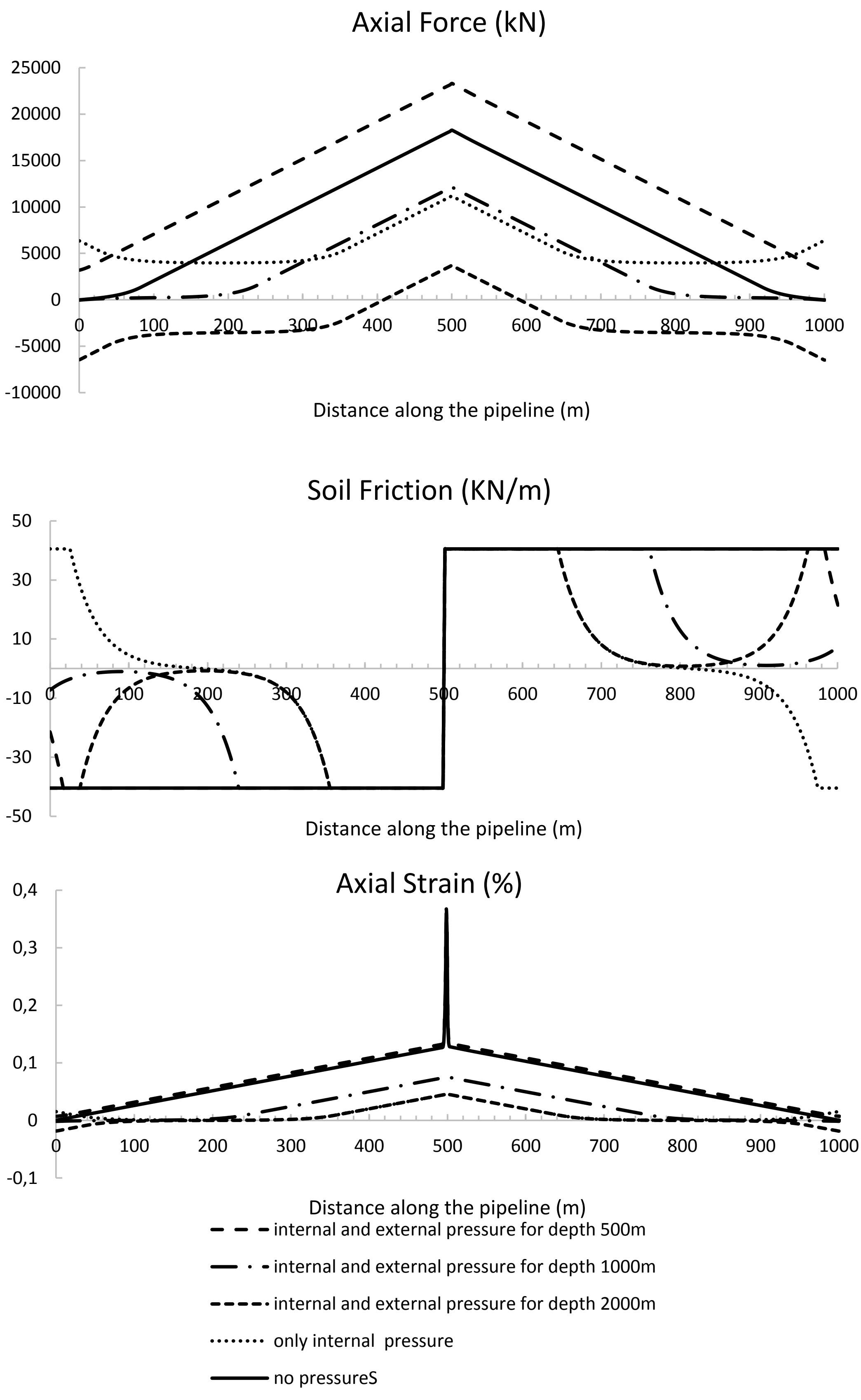


Fig. 4. 13 Axial Force, Soil Friction and Axial strain along the length of the pipeline; intersection with a normal fault

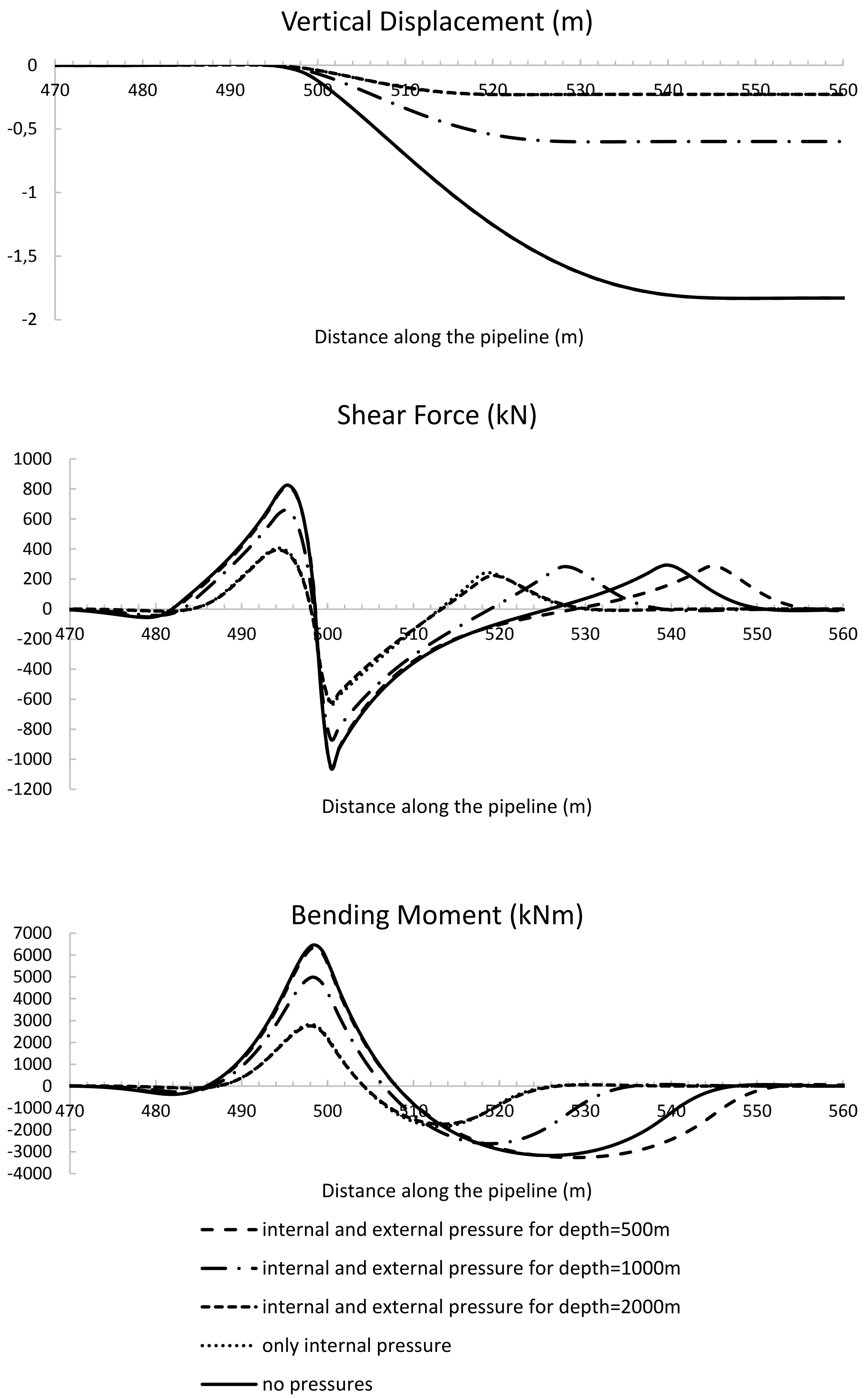


Fig. 4. 14 Vertical displacement, shear force and bending moment along the length of the pipeline

The variation of vertical displacements, shear forces, bending moments, soil resistance and bending strains along the length of the pipeline are presented in Fig. 4. 14 and Fig. 4. 15. When the pipeline is subjected to large external pressures, the vertical displacement of the pipe, as well as the bending strains, reduce substantially. The “curved length” of the pipeline also gets smaller. Generally, we can reach the conclusion that the pipeline is subject to larger strains at smaller depths.

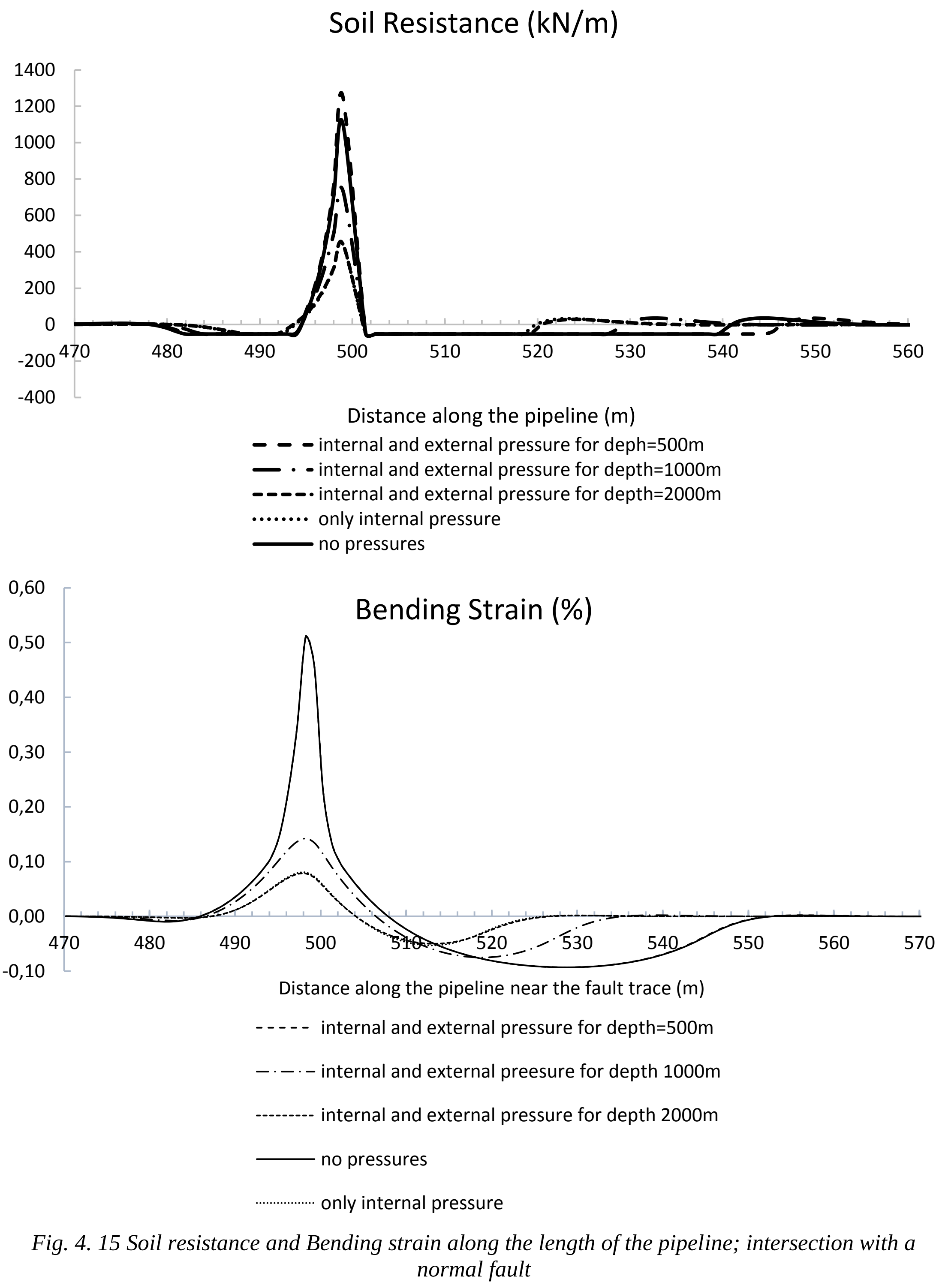


Fig. 4. 15 Soil resistance and Bending strain along the length of the pipeline; intersection with a normal fault

4.3.3 The effect of the soil springs properties

Moreover, a series of analyses were conducted to ascertain the effect of the characteristics of the surrounding soil of the pipeline. The properties of the vertical upward and downward soil springs were adjusted, assuming that the pipeline is buried under clay, with friction angle φ=30° and dry unit weight γ=18 kN/m^3, and very hard rock with friction angle φ=36°, cohesion c=80 kPa and dry unit weight γ=22 kN/m^3. The properties of the soil springs were derived from the ALA guidelines, as listed in Table V. The axial and horizontal springs were kept the same as described in section 4.1. All models were analyzed for a fault offset of Δf=2.0D in an intersection with a normal fault.

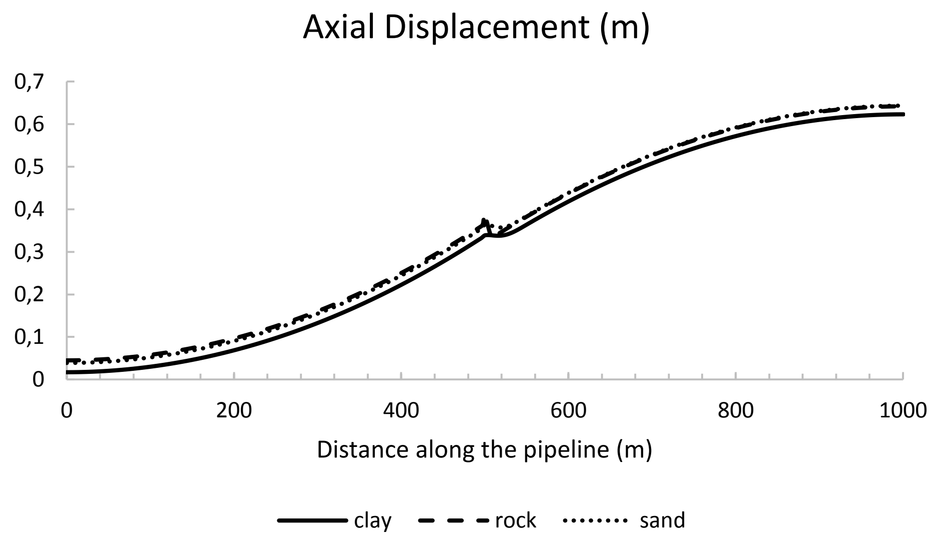
TABLE V
SOIL SPRINGS PROPERTIES

Soil	Spring type	Yield force (kN/m)	Yield displacement (mm)
Medium density sand	Vertical (upward displacement)	52.0	2.2
	Vertical (downward displacement)	1360.0	100.0
Clay	Vertical (upward displacement)	38.95	35.14
	Vertical (downward displacement)	763.52	91.44
Rock	Vertical (upward displacement)	336.73	17.57
	Vertical (downward displacement)	5751.25	182.88

The variation of the axial displacements and axial forces for the different soil materials are presented in Fig. 4. 16. As expected, with rock as soil material, the axial displacements of the pipe are larger and the axial forces present a peak value at the intersection with the fault reaching 20,600 kN.

The variation of the axial strains of the pipeline for the different soil materials are presented in Fig. 4. 17. It becomes evident that in the case of rock as bedrock material the axial strains are extremely large, reaching almost 2.5%, seven times greater than the corresponding strains in other cases with clay and sand as bedrock material. Medium density sand also causes greater strains than the corresponding case of clay, which due to its softness can absorb a lot of the stresses imposed on the pipeline.

It is important to notice that, in the bedrock there might be a very large variety of materials and morphology which are unknown especially in great depths. The pipeline may also be buried under a small amount of soft soil material that is removed with the sea current.



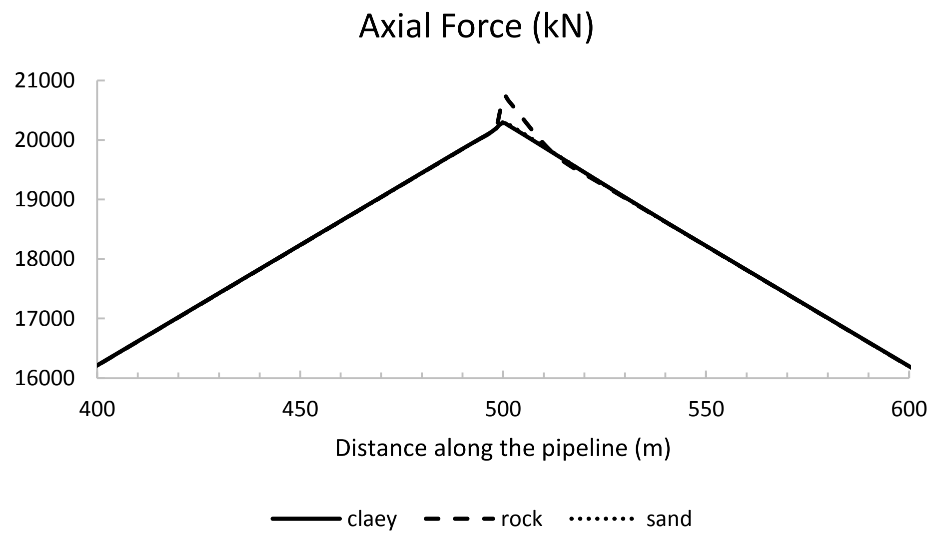
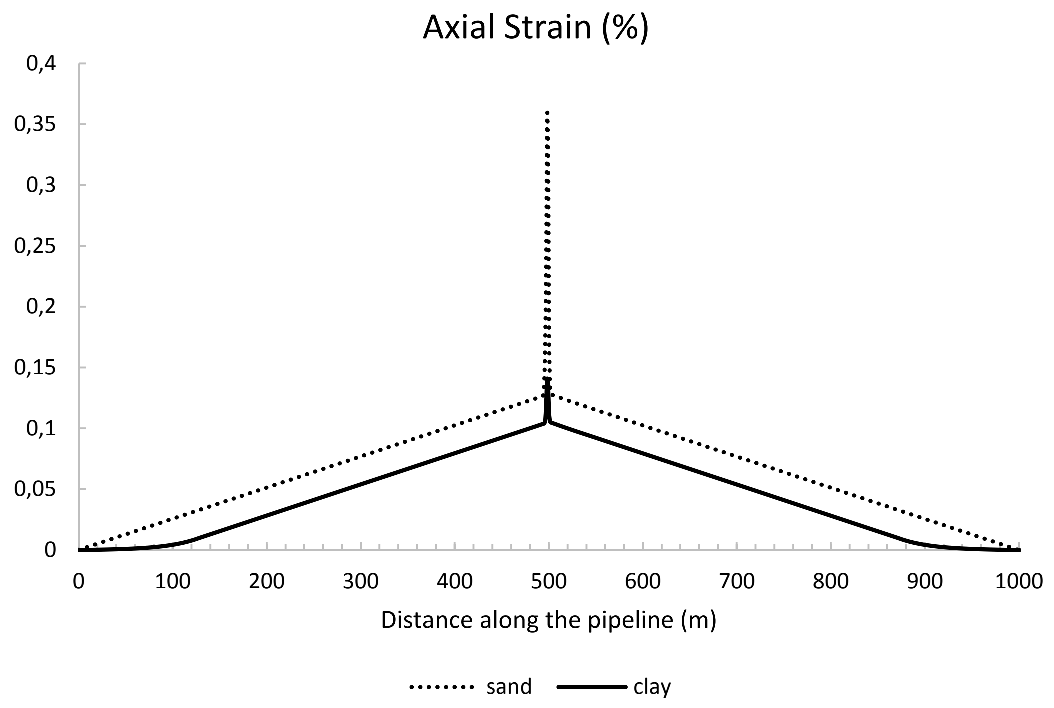


Fig. 4. 16 Axial displacement and axial force along the length of the pipeline; intersection with a normal fault



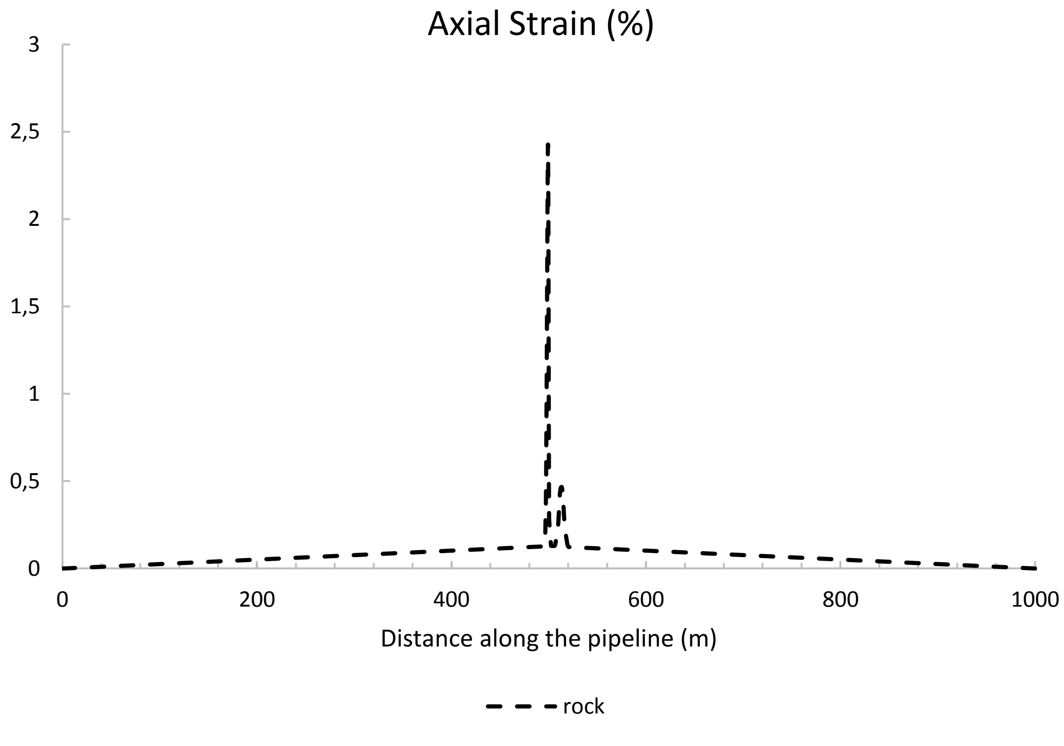


Fig. 4. 17 Axial strains along the length of the pipeline for sand, clay and rock; intersection with a normal fault

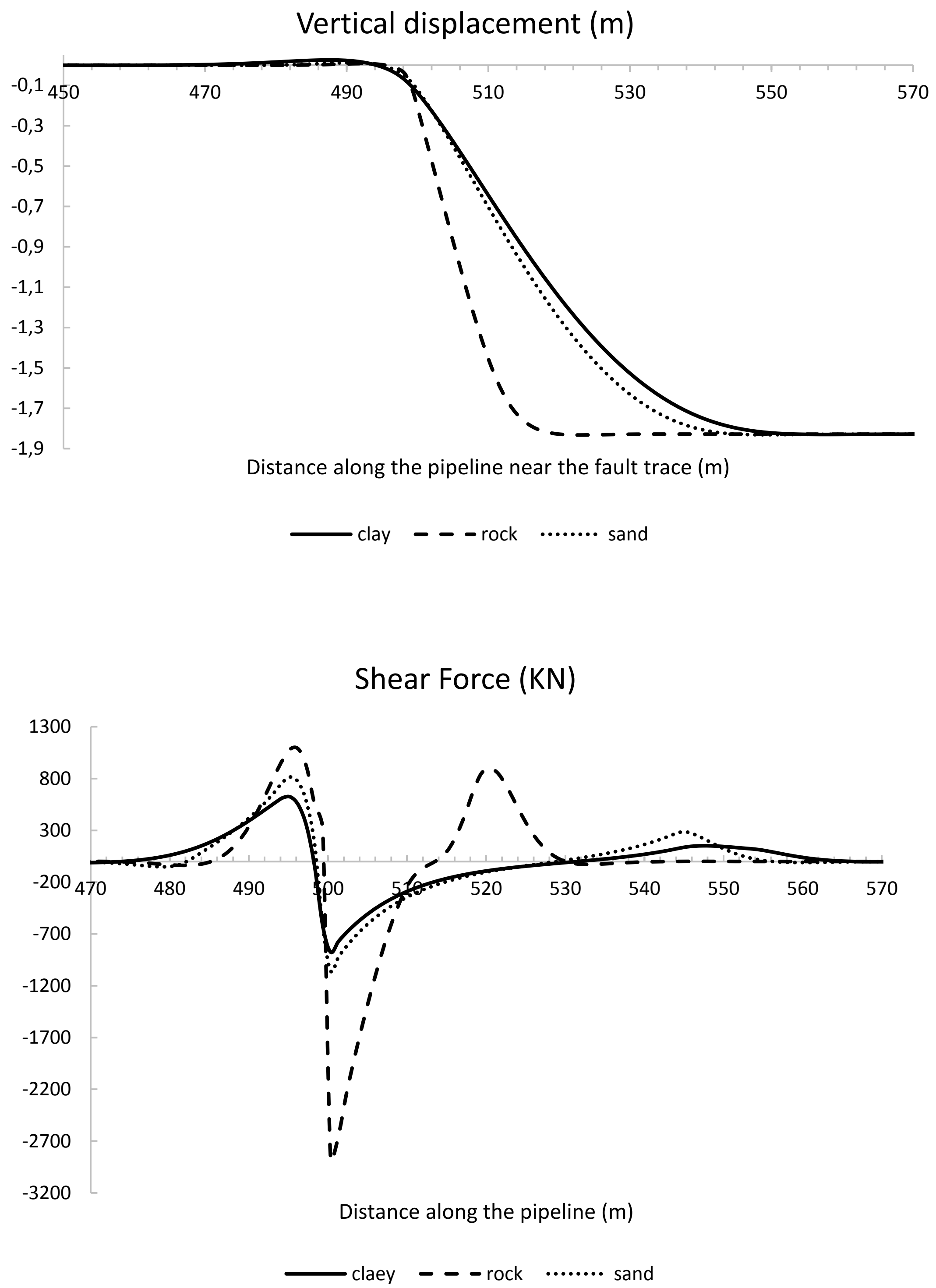


Fig. 4. 18 Vertical displacement and shear force along the length of the pipeline for different soil materials; intersection with a normal fault

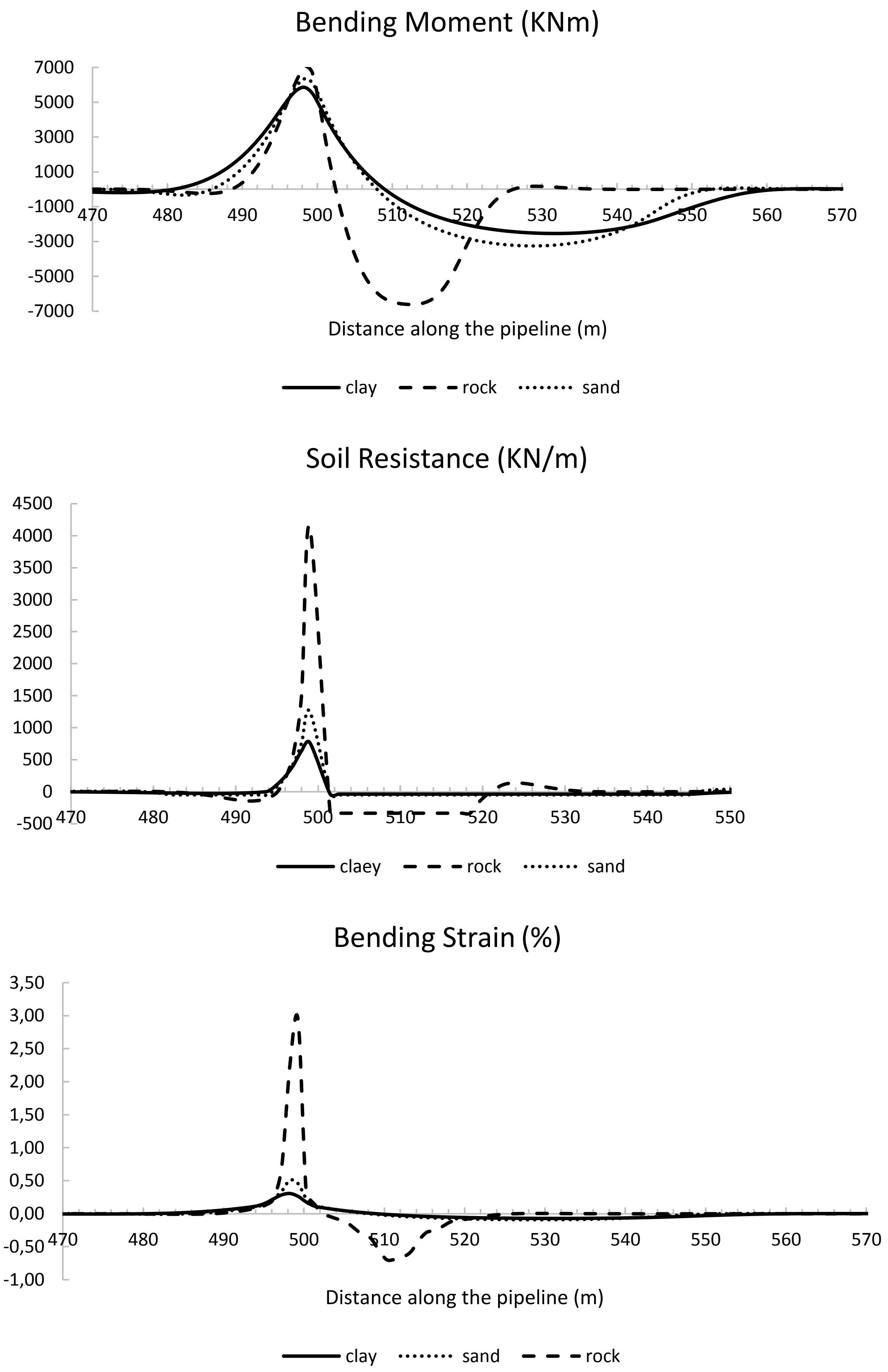


Fig. 4. 19 Bending moment, soil resistance and bending strains along the length of the pipeline for different soil materials; intersection with a normal fault

The variation of the vertical displacements and shear forces along the length of the pipeline for the different soil materials are presented in Fig. 4. 18. As expected, with rock as soil underlay the vertical displacements are more abrupt following the movement of the fault. On the other hand, softer soil materials under the pipeline, in the case of a fault rupture result in a more even distribution of the vertical displacements to the pipeline. The shear forces also present different distribution along the pipeline presenting much greater values.

The variation of the bending moment, the soil resistance and the bending strains along the length of the pipeline for the different soil materials are presented in Fig. 4. 19. Soil resistance presents greater values in the case of rock that creates greater bending strains on the same points as soil resistance. With clay as bedrock, the pipeline is subjected to smaller bending strains, almost 0.27%, with sand almost 0.46% while with rock, bending strains reach 3.0%, a lot more than the yield strain of the pipeline.

4.3.4 The effect of the pipe's wall thickness

Finally the pipe's wall thickness was studied for two different values of thickness t=27mm and t=11.9mm in order to investigate the effect of the subject factor to the distress of the pipeline crossing a fault. Both cases were studied under a fault offset of Δf=2.0D at an intersection with a normal fault. The variation of the axial strains and bending strains along the length of the pipeline are presented in Fig. 4. 20. It is obvious that in case of a thicker pipeline there is a reduction of the strains subjected to the pipeline. The maximum value of axial strain for a pipe wall thickness of t=27mm is 0.3% while for t=11.9mm is 1.1%, a much greater value. Accordingly, for bending strains, the maximum value for a pipe wall thickness of t=27mm is 0.46% while for t=11.9mm is 1.17%.

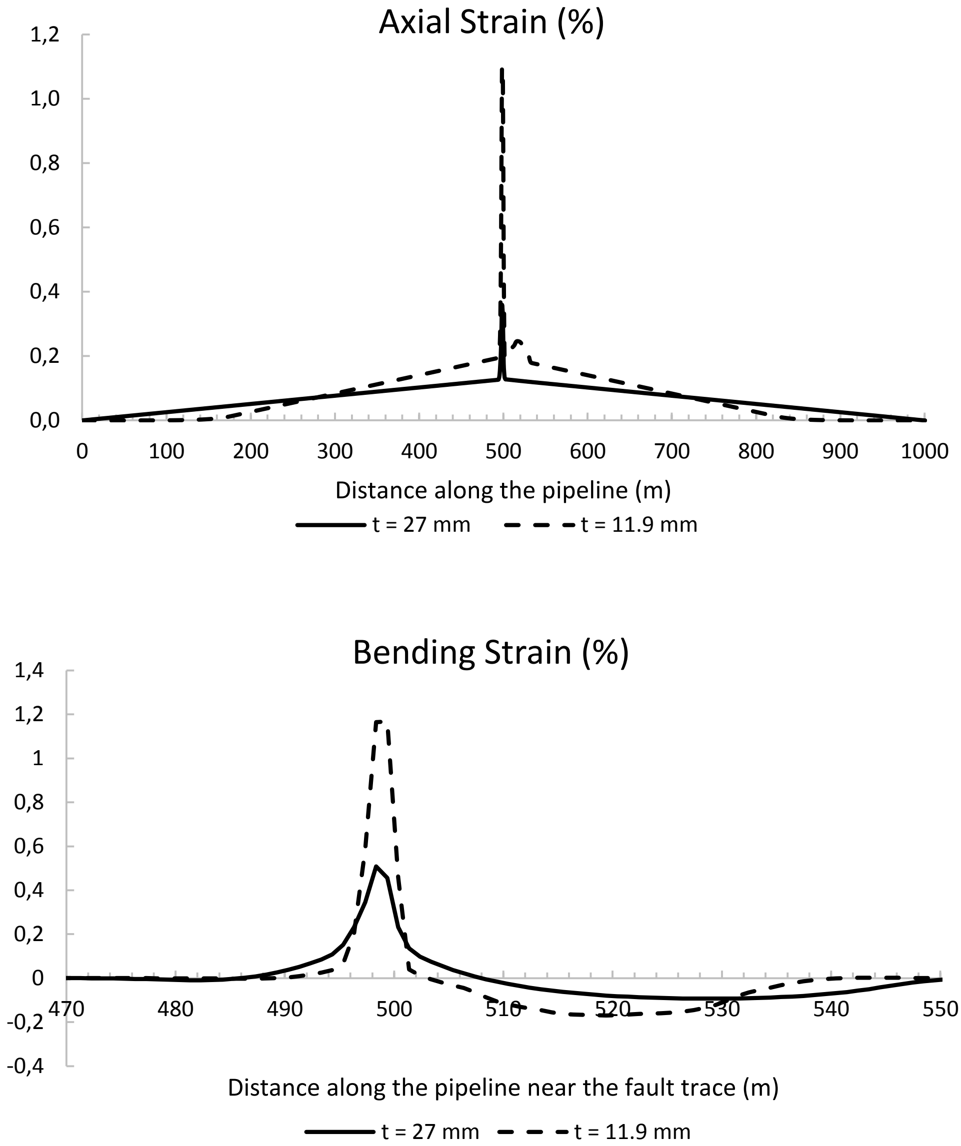


Fig. 4. 20 Axial and bending strains along the length of the pipeline for different pipe’s wall thickness; intersection with a normal fault

5. Conclusions and potential mitigation measures

The current study refers to the issue of offshore pipelines intersecting active seismic faults, and the risks that may arise. Through a parametric numerical analysis the most influencing factors for the integrity of the pipeline are explored, demonstrating the vulnerability of pipelines to fault crossings.

In areas where the route of the pipeline intersects with an active fault, the relocation of the pipeline to avoid the critical area would be an option. However, since the pipeline relocation may be impractical or even impossible for various reasons, mitigation and/or protection measures should be adopted aiming to eliminate or reduce the imposed pipeline distress to acceptable levels.

The design of mitigation measures is a very important issue. It is evident that the adopted measures should be verified by detailed geotechnical investigation and simulations on a case-by-case basis. Depending on the special characteristics of the fault, the selection of any mitigation or protection measure should take into consideration various parameters, such as environmental impact, constructability, accessibility, cost, etc. In the case of crossing a potentially active fault, an increase in pipe wall thickness could be adopted. This measure will increase the capacity of the pipeline to withstand fault movement at a given level of maximum strain as proved by the parametric analysis performed in the current study. On each side of the fault, relatively thick-walled pipe segments should be used. If a slight relocation of the pipeline is possible, then the segment of the pipeline crossing the fault should be oriented in such a way as to place the pipeline in tension (and not in compression, which may additionally cause buckling effects).

List of references

[1] ABAQUS, Users' Manual, Simulia, Providence, RI, USA, 2014.

[2] Abdoun T. H., Ha, D., O'Rourke, M. J., Symans, M. D., O'Rourke, T. D., Palmer, M. C., and Stewart, H. E., "Factors influencing the behavior of buried pipelines subjected to earthquake faulting.", *Soil Dynamics and Earthquake Engineering*, Elsevier, Vol. 29, pp. 415– 427, 2009.

[3] Ambraseys, N. & Jackson, J., "Seismic Movements, Ground Movements and their Effects on Structures", Ed. P. B. Attewell and R.K. Taylor, New York: Surrey University Press, pp. 353-380, 1984.

[4] American Lifelines Alliance – ASCE, Guidelines for the design of buried steel pipe, 2001.

[5] American Petroleum Institute, Recommended practice 1111, fourth edition, Design, Construction, Operation and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design), December 2009.

[6] Anastasopoulos I., "Fault rupture-soil-foundation-structure interaction", Doctoral Dissertation, National Technical University of Athens, 2005.

[7] Arifin R. B., Shafrizal W. M., Wan B., Yusof M., Zhao P., and Bai Y. "Seismic analysis for the subsea pipeline system.", Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2010-20671, Shanghai, China, 2010.

[8] Bai Y., Bai Q., "Subsea Pipelines and Risers", Elsevier, 2005.

[9] Barka A. and Reilinger R., "Active tectonics of the Eastern Mediterranean region: deduced from GPS, neotectonic and seismicity data", *Annali di Geofisica*, Vol. XL, N. 3, 1997.

[10] Bonilla, M.G., "Surface faulting and related effects", *Earthquake engineering*, R. L. Weigel, ed., Prentice Hall, Englewood Cliffs, N.J., 47-74, 1970.

[11] Boyun Guo, Shanhong Song, Ali Ghalambor and Tian Ran Lin, "Offshore Pipelines. Design, Installation, and Maintenance", Elsevier, 2014.

[12] Bray J.D., "Developing mitigation measures for the hazards associated with earthquake surface fault rupture", *Seismic Fault Induced Failures*, 2001.

[13] DNV, Offshore Standard-F101, Submarine pipeline systems, 2012

[14] E.T.R. Dean, "Offshore Geotechnical engineering", Principles and practice, Thomas Telford Limited, 2010.

[15] Eurocode 8, Design of structures for earthquake resistance, Part 4: Silos, tanks and pipelines, CEN-ENV, European Committee for Standardization, Brussels, 2006.

[16] Finetti I.R., "Deep Seismic Exploration of the Central Mediterranean and Italy", CROP Project, *Atlases in Geoscience*, Vol. 1, Elsevier, 2006.

[17] Guo B., Song S., Chacko J., Ghalambor A., "Offshore Pipelines", Elsevier, 2005.

[18] Hamada, M. "Measures and designs of lifelines against fault-induced ground surface ruptures," *Seismic Fault Induced Failures*, Workshop, JSCE (Konagai, K., Hori, M., Meguro, K. and Koseki, J., eds.), pp. 119–130, 2003.

[19] Hobbs B., Means W., Williams P., "Joints and faults, an outline of structural geology", John Willey and sons, Inc., pp. 300-345, 1976.

[20] IITK-GSDMA, Guidelines for seismic design of buried pipelines, NICEE, India, 2007.

[21] ISO 19901-2, Petroleum and natural gas industries-Specific requirements for offshore structures, Part 2- Seismic design procedures and criteria, 2004.
[22] Karamitros D., Bouckovalas G., Kouretzis G., "An analytical method for strength verification of buried steel pipelines at normal fault crossings", Soil Dynamics and Earthquake Engineering, 2011, vol. 31, pp. 1452-1464.
[23] Karamitros D., Bouckovalas G., Kouretzis G., "Stress Analysis of buried Steel Pipelines at Strike-Slip Fault Crossings", Soil Dynamics and Earthquake Engineering, 2007, vol. 27, pp. 200-211.
[24] Kennedy R.P., Chow A.W., Williamson R.A, "Fault movement effects on buried oil pipeline", Journal of the Transportation Engineering Division, ASCE, 1977, vol.103, pp. 617–33.
[25] Konagai K. et al., "Key Points for Rational Design for Civil Infrastructures near Seismic Faults Reflecting Soil-Structure Interaction Features", Report of JSPS research project, grant-in-aid for scientific research (A) Project No.16208048, 2006.
[26] M.W. Braestrup, "Design and Installation of marine pipelines", 2005.
[27] Matsuda, T., "Magnitude and recurrence interval of earthquakes from a fault", J. Seismol. Soc. Jpn., Vol 28, pp. 269-283, 1975.
[28] N.Y. Kershenbauma, S.A. Mebarkia, H.S. Choi, "Behavior of marine pipelines under seismic faults", *Ocean Engineering*, Elsevier, Vol. 27 (2000) pp. 473–487, 1998.
[29] Newmark N.M., Hall W.J., "Pipeline Design to Resist Large Fault Displacement", Proceedings of the 1975 U.S. National Conference on Earthquake Engineering, Ann Arbor, Michigan, pp. 416-425, 1975
[30] O'Rourke MJ, Liu X., Seismic design of buried and offshore pipelines, Monograph Series, Multidisciplinary Center for Earthquake Engineering Research, (MCEER), 2012.
[31] Odina, L. and Conder, R. J., "Significance of Lüder's Plateau on Pipeline Fault Crossing Assessment", Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2010-20715, Shanghai, China, 2010.
[32] Odina, L. and Tan, R., "Seismic Fault Displacement of Buried Pipelines Using Continuum Finite Element Methods", Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2009-79739, Honolulu, Hawaii, 2009.
[33] Psarropoulos P. et al., "The impact of earthquake-related geohazards on offshore pipelines and seaside facilities of the oil & gas industry in the Mediterranean region", Proceedings of the Fourteenth International Conference on Civil, Structural and Environmental Engineering Computing, B.H.V. Topping and P. Iványi, Civil-Comp Press, Stirlingshire, Scotland, 2013.
[34] Sim W.W., Towhata I., Yamada S., Moinet G.J.-M., "Shaking table tests modeling small diameter pipes crossing a vertical fault.", *Soil Dynamics and Earthquake Engineering*, Elsevier, Vol. 35, pp. 59-71, 2012.
[35] Takada, S., Hassani, N.and Fukuda, K. (2001), "A new proposal for simplified design of buried steel pipes crossing active faults", *Earthquake Engineering and Structural Dynamics*, Vol.30: pp.1243–1257, 2001.

[36] Towhata, I., “Geotechnical Earthquake Engineering”, Springer, pp. 315-339, 2008.
[37] Trifonov OV, Cherniy VP, “Elastoplastic stress–strain analysis of buried steel pipelines subjected to fault displacements with account for service loads”, Earthquake Engineering and Structural Dynamics, 2012, vol. 33, pp. 54-62.
[38] Trifonov OV, Cherniy VP., “A semi-analytical approach to a nonlinear stress-strain analysis of buried steel pipes crossing active faults”, Earthquake Engineering and Structural Dynamics, 2010, vol. 30(11), pp. 1298-208.
[39] Trimintziou M.S., Sakellariou M.G., Psarropoulos P.N., “Designing offshore pipelines facing the geohazard of active seismic faults”, Proceedings of the 17th International Conference on Ocean, Offshore and Arctic Engineering, *World Academy of Science, Engineering and Technology*, Tokyo, Japan, 28-29 May 2015.
[40] Vazouras P., Karamanos S. A., Dakoulas P., “Mechanical behavior of buried steel pipes crossing active strike-slip faults”, *Soil Dynamics and Earthquake Engineering*, Elsevier, Vol. 41, pp. 164-180, 2012.
[41] Vazouras P., Karamanos S. A., Dakoulas P.,”Finite element analysis of buried steel pipelines under strike-slip fault displacements.”, *Soil Dynamics and Earthquake Engineering*, Elsevier, Vol. 30, pp. 1361–1376, 2010.
[42] Wang L.R.L., Yeh Y., “A refined seismic analysis and design of buried pipeline for fault movement”, Journal of Earthquake Engineering and Structural Dynamics, 1985, vol. 13, pp. 75–96.

Appendix A

CODES REGARDING ONSHORE PIPELINES CROSSING SEISMIC FAULTS

1. EUROCODE 8: “Design of structures for earthquake resistance - Part 4: Silos, tanks and pipelines”

This standard specifies principles and application rules for the seismic design of the structural aspects of facilities composed of above-ground and buried pipeline systems. Furthermore, it includes the additional criteria and rules required for the seismic design of these structures without restrictions on their size, structural types and other functional characteristics.

Concerning the specific principles and application rules for buried pipelines, according to Eurocode 8, buried pipeline systems should be designed and constructed in such a way as to maintain their integrity or some of their supplying capacity after the seismic events relevant to the damage limitation state, even with considerable local damage. Generally, it is acceptable to take advantage of the post-elastic deformation of pipelines. The deformation capacity of a pipeline should be evaluated.

More precisely, the seismic design of buried pipeline systems should take into account the following direct and indirect seismic hazard types:

a) seismic waves propagating on firm ground and producing different ground shaking intensity at distinct points on the surface and spatial soil deformation patterns within the soil medium;

b) permanent deformations induced by earthquakes such as seismic fault displacements, landslides, ground displacements induced by liquefaction.

In Eurocode 8, some design measures for pipelines potentially crossing active faults are proposed. The decision to apply special fault crossing designs for pipelines where they cross potentially active fault zones depends upon cost, fault activity, consequences of rupture, environmental impact and possible exposure to other hazards during the life span of the pipeline.

In the design of a pipeline for fault crossing, according to Eurocode 8, the considerations written below, would generally improve the capability of the pipeline to sustain differential movements along the fault.

1. Where practical, a pipeline crossing a strike-slip fault should be oriented in such a way as to place the pipeline in tension.
2. The angle of intersection of reverse faults should be as small as possible, to minimize compression strains. If significant strike-slip displacements are also anticipated, the fault crossing angle of the pipeline should be chosen to promote tensile elongation of the line.
3. In fault zones the depth at which the pipeline is buried should be minimized in order to reduce soil restraint on the pipeline during fault movement.
4. An increase in pipe wall thickness will increase the pipeline's capacity for fault displacement at a given level of maximum tensile strain. Within 50 m on each side of the fault relatively thick-walled pipe should be used.
5. Reduction of the angle of interface friction between the pipeline and the soil increases the pipeline's capacity for fault displacement at a given level of

maximum strain. The angle of interface friction can be reduced through a hard, smooth coating.

6. Close control should be exercised over the backfill surrounding the pipeline over a distance of 50 m on each side of the fault. In general, a loose to medium granular soil without cobbles or boulders will be a suitable backfill material. If the existing soil differs substantially from this, oversize trenches should be excavated for a distance of approximately 15 m on each side of the fault.
7. For welded steel pipelines, fault movement can be accommodated by utilizing the ability of the pipeline to deform well into the inelastic range in tension, in order to conform without rupture to the ground distortions. Wherever possible, pipeline alignment at a fault crossing should be selected such that the pipeline will be subjected to tension plus a moderate amount of bending. Alignments which might place the pipeline in compression should be avoided to the extent possible, because the ability of the pipeline to withstand compressive strain without rupture is significantly less than that for tensile strain. Any compressive strains should be limited to that strain which would cause wrinkling or local buckling of the pipeline.
8. In all areas of potential ground rupture, pipelines should be laid in relatively straight sections, avoiding sharp changes in direction and elevation. To the extent possible, pipelines should be constructed without field bends, elbows and flanges that tend to anchor the pipeline to the ground.

Depending on the circumstances, the solution may require either increasing the burial depth, possibly also encasing the pipes in larger stiff conduits, or in placing the pipeline above-ground, supporting it at rather large distances on well-founded piers. In the latter case flexible joints should also be considered to allow for relative displacements between supports.

Design for fault movements requires estimating, sometimes postulating, a number of parameters including: location, size of the area affected, type and measure of the fault displacement. Given these parameters, the simplest way of modelling the phenomenon is to consider a rigid displacement between the soil masses interfacing at the fault.

The general criterion for minimizing the effect of an imposed displacement is that of introducing the maximum flexibility into the system which is subjected to it.
In the case under consideration this can be done:

a. by decreasing the burial depth so as to reduce the soil restraint;
b. by providing a large ditch for the pipes, to be filled with soft material;
c. by putting the pipeline above ground, and introducing flexible and extensible piping elements.

2. INDIAN-NICEE: "Guidelines for seismic design of buried pipelines"

This document deals with the seismic design requirements for new continuous and segmented buried pipelines. It can also be used as a basis for evaluating the level of strengthening or increased redundancy needed by existing facilities to improve their response during seismic events. This document covers design criteria for buried pipelines for various seismic hazards such as: wave propagation, fault crossing, and permanent ground deformation (PGD) due to liquefaction, lateral spreading, etc.

Concerning the safety requirements, according to this standard, the location of the pipeline, the size of the population that is exposed to the impact of the pipeline rupture, and the environmental damage due to the pipeline rupture should be considered in establishing the level of acceptable risk while designing the pipeline system.

Generally the oil and gas pipelines are designed and constructed as continuous pipelines, while water supply pipelines are constructed as segmented pipelines.

The design criteria for a pipeline crossing a fault of expected ground movement according to the INDIAN-NICEE guideline are presented below:

1. The pipeline crossing fault line should be oriented in such a way to avoid compression in the pipeline. The optimum angle of fault-crossings will depend on the dip of the fault plane and the expected type of movement.
2. The ductility of pipeline should be increased in the zone of fault-crossing to accommodate the fault movement without rupture.
3. Abrupt changes in wall thickness or other stress concentrators should be avoided within the fault zone.
4. In all areas of potential ground rupture, pipelines should be laid in relatively straight section avoiding sharp changes in direction and elevation.
5. To the extent possible, pipelines should be constructed without field bends, elbows, and flanges that tend to anchor the pipeline to the ground.
6. If longer length of pipeline is available to conform to fault movement, level of strain gets reduced. Hence, the points of anchorage should be provided away from the fault zone to the extent possible in order to lower the level of strain in the pipeline.
7. A hard and smooth coating on pipeline such as an epoxy coating may be used in the vicinity of fault crossing to reduce the friction between the pipe and soil.
8. The burial depth of pipeline may be reduced within fault zones in order to minimize the soil restraint on the pipeline during fault movement.
9. If the expected fault displacement is very large, it is advisable to take the pipeline above ground and design with sliding supports to sustain the expected level of ground displacement.

Quantification of Fault Displacement according to INDIAN-NICEE

Evaluating the expected fault displacement requires specialized and rigorous analysis. In the absence of such an analysis, available site specific empirical relationship may be used. One of the widely used empirical relationships is the one that was given by Wells and Coppersmith (1994). Based on worldwide database of 421 historical earthquakes, Wells and Coppersmith selected 244 earthquakes and developed empirical relationship between fault displacement and moment magnitude. As per their observation, fault displacement varies from 0.05 to 8.0 m for strike slip faults, 0.08 to 2.1 m for normal faults, and 0.06 to 1.5 m for reverse faults.

According to that the fault displacement can be evaluated as follows:

- For a strike-slip fault: $\log \delta_{fs} = -6.32 + 0.90M$
- For a normal fault: $\log \delta_{fn} = -4.45 + 0.63M$
- For a reverse fault: $\log \delta_{fr} = -0.74 + 0.08M$
- For a poorly known fault or blind fault: $\log \delta_{fb} = -4.80 + 0.69M$

Where,

δ_{fs} = Strike slip fault displacement in meters

δ_{fn} = Normal slip fault displacement in meters
δ_{fr} = Reverse slip fault displacement in meters
δ_{fb} = Displacement of a blind fault in meters
M = Moment magnitude of earthquake

For a **strike slip fault** (Fig. A. 1), the fault movement along and transverse to the pipeline may be calculated as follows:
The component of the fault displacement in the axial direction of the pipeline is:

$$\delta_{fax} = \delta_{fs} \cos\beta$$

The component of the fault displacement in the transverse direction of the pipeline is:

$$\delta_{ftr} = \delta_{fs} \sin\beta$$

Where,
β = angle of the pipeline crossing a fault line (Fig. A. 1)

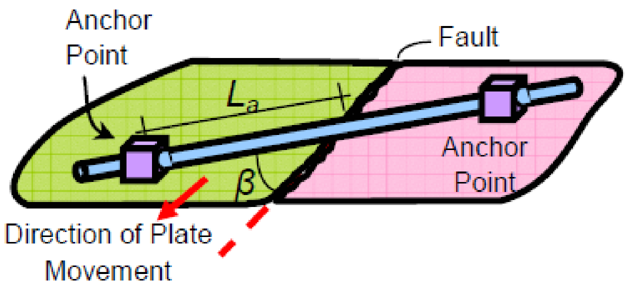


Fig. A. 1 Pipeline crossing a strike slip fault.

For a **normal slip fault** (Fig. A. 2), the fault movement along, transverse and vertical to the pipeline may be obtained as follows:
The component of the fault displacement in the axial direction of the pipeline is:

$$\delta_{fax} = \delta_{fn} \cos\psi \sin\beta$$

The component of the fault displacement in the transverse direction of the pipeline is:

$$\delta_{ftr} = \delta_{fn} \cos\psi \cos\beta$$

The component of the fault displacement in the vertical direction of the pipeline is:

$$\delta_{fvt} = \delta_{fn} \sin\psi$$

Where,
β = angle of the pipeline crossing a fault line
ψ = Dip angle of the fault

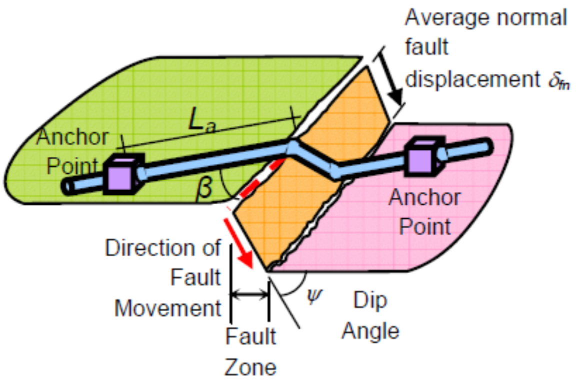


Fig. A. 2 Pipeline crossing a normal slip fault.

In **reverse faults**, the displacement components are evaluated in the similar way as in normal-slip faults, but, with a negative slip.

For **oblique faults**, the strike slip displacement and normal slip (or reverse slip) displacement may be added algebraically in axial, transverse and vertical direction of the pipeline axis.

To achieve minimum soil resistance to reduce the strain in pipe, the pipeline can be buried in a shallow trench as shown in Fig. A. 3 and Fig. A. 4 with loose to medium granular soil without cobbles or boulders. Close control must be exercised over the backfill material of the pipe trench over a considerable distance (~300m) on each side of the fault.

Good geotextile membrane may be used in between native and backfill soil (i.e., over the trench wall). This will prevent mixing of the fines from native soil with the well graded backfill material for a long period of time.

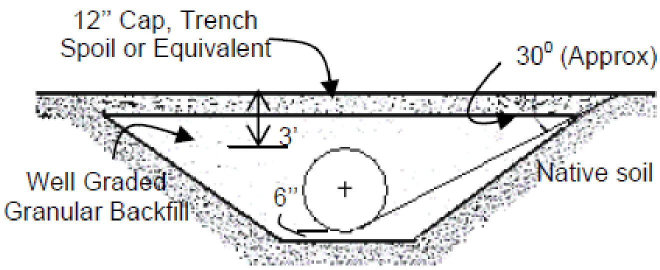


Fig. A. 3 Pipeline trench for strike slip fault crossing (NIST, 1996).

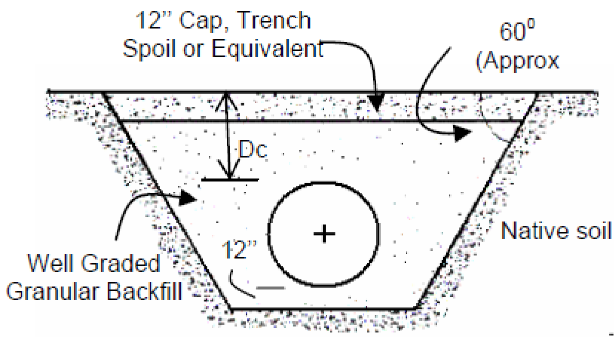


Fig. A. 4 Pipeline trench for reverse slip fault crossing (NIST, 1996).

Finally this standard concludes that the above analytical procedure of designing pipelines crossing active faults is based on simplified Newmark–Hall's model and it may be followed to estimate the design values of first order approximation. A nonlinear finite element based analysis is hence recommended for detailed analysis and design, models of which are also included in this standard.