DYNAMIC PREDICTION AND EARTHQUAKE MONITORING – ONE OF POSSIBLE APPROACHES TO DECREASE THE RISK FOR OIL AND GAS PIPELINE

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ABSTRACT :
During global industrial development of oil and gas fields in any seismoactive region designing of the main oil and gas pipeline is particularly important for the assessment seismic hazards in these regions. This is one of the important tasks during antiseismic construction and for environmental protection. It is possible to prevent and minimize possible losses by means of normative maps of seismic zonation designated for the Caspian basin and for oil and gas pipeline routes. At present these maps significantly underestimate the region's hazard and current construction works are being performed without the proper assessment of this region's seismicity. It is possible to solve problems on assessment of seismicity on new conceptual base by methods of dynamic earthquake prediction. Such a long-time dynamic earthquake prediction for the Caspian Sea - Eastern Turkey - Iran region was based on systemic seismogeodynamic approach to investigation of earthquake focal zones and on block model of seismokinematics of this region. The resulting map of dynamic regionalisation of the degree of seismic hazards up to year 2006 predicted not only place and strength of potential zones of the strongest earthquakes, but also the periods of increased probability of their occurrence within the source volume of the future mainshock. An early warning system of automatic telemetry have to be set up along with local and regional monitoring networks to predict short and medium term seismic hazard zonation the international earthquake monitoring and forecasting network. Economically, continuous operation of large pipelines is extremely important because of the huge energy content of the oil flow. The earthquake detection system presented here consists of accelerometers, which measure the immediate effects of the earthquake, and pipeline deformation sensors, which detect secondary impacts to the pipeline.

KEYWORDS:
Seysmicity, monitoring, pipeline, prediction

1. BAKU – TBILISI – CEYHAN PIPELINE: DEALING WITH EARTHQUAKES

The BTC pipeline route crosses the seismically active Trans-Caucasus region of Azerbaijan and Georgia, and the seismically active terrain of Turkey. The whole region forms part of the Alpine-Himalayan fault and fold belt, which stretches from the Swiss Alps through to the Himalayan ranges of India and Nepal. The active belt is being deformed by the collision of African, Arabian and Indian tectonic plates. Several active faults are crossed along the route. There are three fault crossing in Azerbaijan, three in Georgia and seven in Turkey. To design the pipeline crossing in the these regions, and specifically the active faults, the BTC project has used the specialist skills of companies like ASC consulting and DJ Nyman and Associates who specialize in seismic hazards assessment and fault crossing evaluation.
Here is the summarizes the work done over last 10 years regarding the development of new approaches for earthquake risk mitigation. The methods of mitigation of damage from earthquakes include assessment of seismic hazard, dynamic prediction of earthquakes, analytical calculations of numerical models, microseismic zonation, etc. The approaches are demonstrated, accordingly, on examples of azeri part of test

area "Caucasus", the Caucasian-Caspian Iranian East Anatolian region, Absheron peninsula and Baku city.
Given that these important facilities are situated in a highly seismic zone the proposed research will focus on the following aspect: safety of oil prospecting in the Caspian basin and protection of the capital investment while placing high importance in the environmental management. The oil supply line crosses the seismically active system of deep faults of the Absheron-Cheleken sill, the western part of Azerbaijan near the seismically active focal zone of Gyandja and traverses most of the seismic active zone of the Anatolian-Caucasus-Iran tectonic knot. Magnitude M=8 earthquakes have occurred along this oil pipeline route. The schematic map of seismic zonation for Azerbaijan territory (1990), maps of seismic hazard and assessment of maximal magnitudes using the independent methods (including Probabilitic and computer calculations with package Seisrisk) as well as on the base of uniform earthquake catalogue and active faults model of seismic source zone (SSZ) were presented as results of carried done works.
Peak horizontal ground acceleration is chosen as a parameter representing seismic hazard and the period of repetition in years for values of accelerations is given. The prediction values on map of maximal magnitudes of SSZ were further in good accordance with real observations of two earthquakes occurred in Baku city on November 25, 2000 with M 5.8 and 6.3 (A.Martirosyan, S.Balassanian et al., 1999). The strong-motion predictions in the Absheron peninsula including Baku city were researched by using database on dynamic and spectral characteristics of grounds of close earthquakes, geological and velocity models of structure of surface sedimentary deposits. Besides, numerical modeling of target earthquakes by near, far, and local events expressed in peak ground acceleration value compared to intensity MSK-64 scale was made for Absheron peninsula and Baku, a numerical modeling of amplification factor was plotted that gives the possibility for estimating a level of seismic motion and the visual seismic intensity picture of the researched area.
The process of numerical modeling was done by visualization GIS based on application techniques applying program such as Shake (Japanese version) and MapInfo professional 4.5 (USA).

2. EARTH'S CRUST FAULT IDENTIFICATION

A new map of deep faults of the earth crust for the territories of different-scale on the example of Azerbaijan, Caspian Sea and Caucasus – Caspian - Iran region has been built (Fig 1). This map shows indicators of their quantitative parameters and seismicity. The methodology of building a generalized network of deep faults and blocks of the earth crust was based on a combined use of anomalies of geophysical fields and material of multiwave deep seismic studies. In addition to linear faults, this map shows concentric accurate and circular faults.
On this map deep faults and blocks of the earth crust are detailed and informative for the oil and gas bearing regions of the Kura depression, as well as foothill areas including the territory of Shemakha-Gobustan area. Justification of tracing of faults and the block with increased velocity values which coincides with the most lifted part of the foundation in the central part of the Kura depression allowed to recommend this block (Saatly) for superdeep drilling with the purpose of opening the basalt-like rocks. We propose principally new 3D seismic method of study of low-rate layers and horizontal heterogeneities fault zone within the Earth crust. Position of the dilatant fault zones of the low-rate velocities of the longitudinal elastic waves (hatched) in the deep fault of the Earth crust were finding in area of drilling of well SG-1 on cross section #30 correlation refraction method. The conception of the sedimentary-stage geodynamics of the Earth rust blocks is substantiated on the base of the above-mentioned data; the crust is established by the existence of inversion dilatant seicmic-velocity zones of decompaction and their interrelation with elastic enclosing layers of the sedimentary basin of the South Caspian depression and adjoining depressions as well.

3. REVEALING AND USE OF STRUCTURE AND DYNAMICS OF THE SEISMICITY

Recently, in the regions of the Mediterranean seismic belt, intensive researches have been carried out on intermediate- and long-term prediction of the location of large earthquakes. This problem can be solved based on various concepts that are confirmed by certain regularities of the spatio-temporal distribution of earthquake. Two approaches have mainly been applied to earthquake prediction. One of them is based on the method of pattern recognition and has been used for separate regions (Gorshkov e*t al.,* 1979). Another fundamentally different approach uses the basic principles of representation such as "seismic quiescence" and "average recurrence time", based on the study of recent and large historical earthquakes (Purcaru and Berckhemcr, 1979, 82).

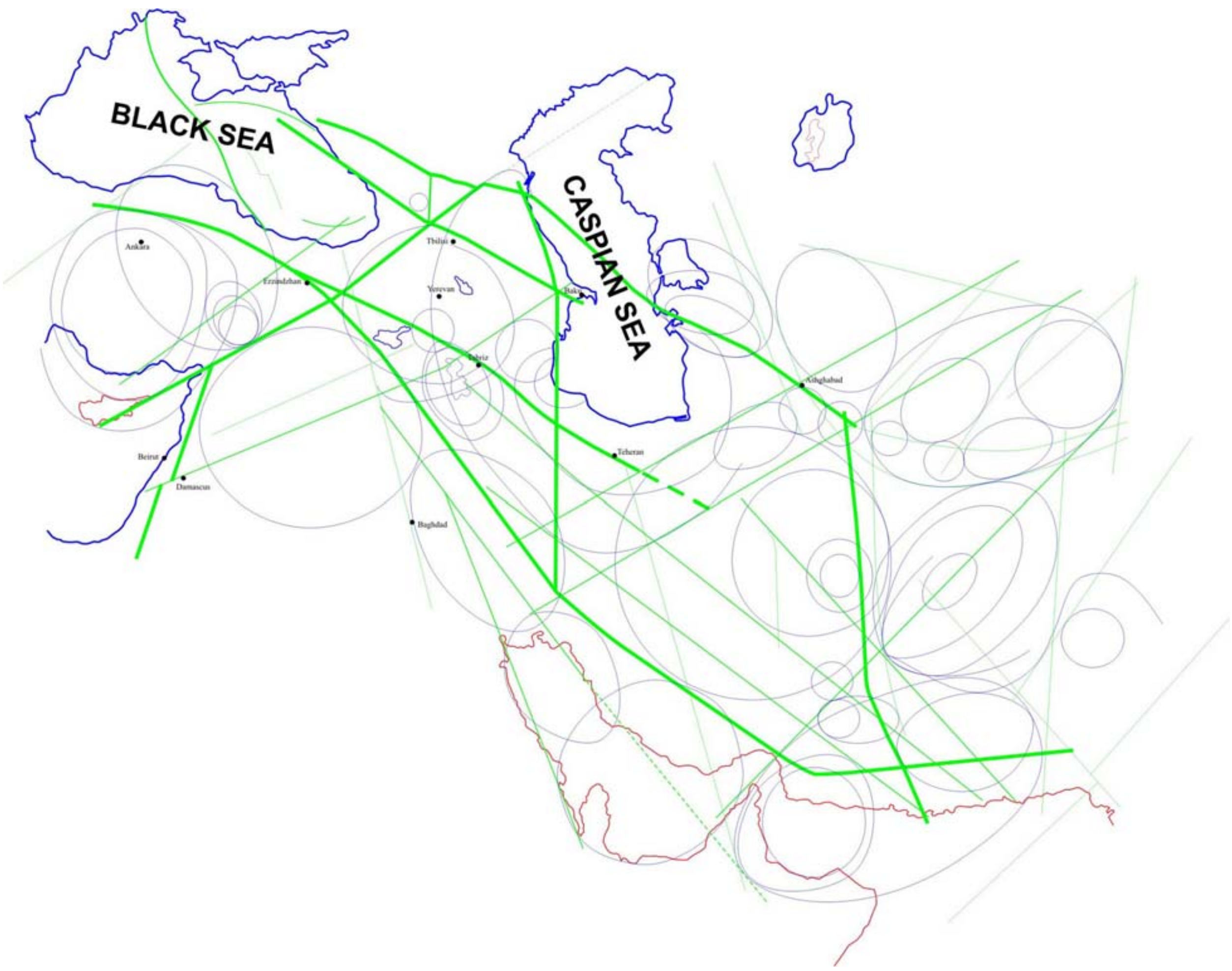

Figure 1. Model of system of the linear and ring faults of the Earth crust of the Caucasus – Iran region by geologic-geophysical anomalies

The latter approach has been adopted in the first systematic investigation of the Mediterranean region as a whole, in terms of the zones of possible occurrences of large earthquakes. However, practically no study has ever been carried out for a considerable part of the region east of Erzinjan (Turkey) in longitude, which presents an equally complex district of interaction between the European and Arabian-Indian plates.

Applying the both approaches, we could carry out successful earthquake prediction without indicating the time of the shock. For individual earthquakes in Caucasus, however, as in the case of the Spitak (Armenia) event, we also predicted the period of enhanced possibility of earthquake occurrence (Keilis-Borok *et al,* 1989).

Since 1985, the author has been engaged in detailed investigations of seismogeodynamics of the seismic zones in the region extending over East Anatolia, Caucasus, Iran, South Caspia and Kopet Dag (Babazade, 1988, 89). Based on the well-known principles of seismic regularities, which have been worked out in the Pacific and Alpine active zones (Fedotov, 1965, 68; Purcaru and Berckhemer, 1979, 82, 84; etc.) and also based on special approaches proposed, we have been predicting here the locations and the time period of expected large earthquakes with $M \geq 6.5$.

Regularities in the spatio-temporal distribution of interrelated earthquakes were searched for by investigating the migration of successive earthquakes and by identifying seismic quiescence zones within each seismic

belt.
The migration of the earthquakes was investigated, based on a systematic catalogue of large earthquakes (M ≥ 5.6) in this region for the time period 1895-1990, which was compiled using elaborated materials for each territory. The sequences of the earthquake distribution were analyzed by the methods of Vil'kovich and Shnirman (1979) and the least squares (Meyer *et al.,* 1984, 85) for eight relatively narrow (100-350 km) seismic belts, which had been picked out in view of their high density of epicenter concentration. As a result, we recognized a regular tendency for a quasi-cyclic migration of earthquakes along the linear seismic belts with various speeds (from 15 to 163 km/yr) and directions. Such a migration can be traced in an example of the projections of earthquake sources in the direction of the axis of the seismic belt III (Babazade O.B., 1991). For identifying seismic quiescence zones (seismic gap of the first kind of K. Mogi) we made use of available historical data concerning earthquakes with M ≥ 6.2 for a longer period (since 400 up to the present). Figure shows a part of the spatio-temporal distribution of large earthquakes along the axis of the seismic belt. If we simultaneously have a look at the diagrams mentioned above for the belts III, VI and VIII, we can foresee occurrence of a large earthquake, based on the past development of seismic activity, its periodicity, and also on the slope of the earthquake migration stripes and the directions of their migration in space. The time periods were estimated graphically using the migration stripes.
We present fragments of the trajectories of earthquake migration and one of the zones where a potential large earthquake was predicted (Babazade, 1992). A large earthquake with M ~ 7.2 occurred at night on June 20, 1990 in the northern and northwestern regions of Iran (East Azerbaijan, Mazandaran, Gilan) on the coast of the Caspian Sea, where a potential possibility of an earthquake had been proposed. This zone, presented in (Babazade O.B., 1991) as a single one, had been recognized, in fact, as two separate districts neighboring each other. The epicenter of the June 20, 1990 earthquake (Rudbar) belongs to the western portion of this zone. The second, eastern portion, including Teheran, still remains unruptured.
The dimension of the zone of future sources had been restricted between 36.5-37.6°N in latitude and 48.8-50.6°E in longitude, and between 35.0-37.6°N and 50.6-52.9°E for the first and second portions respectively. The expected period of possible large earthquakes had been estimated for the first event to be the 5 years from 1986 to 1990 for the belt VIII, and the 2 years 1989-1990 for the belt III, and for the second event to be the 4 years 1989-1992. In these two identified seismic gaps of the first kind, large earthquakes had never occurred since 1678 and 1665 respectively.
A next step was taken with a view to more accurately diagnosing the data concerning the seismic gap of the first kind, which requires identification of phenomena that preceded the earthquake. Among the many studied phenomena that are important as precursors in our contemporary application, seismic gaps of the second kind as Mogi's "doughnuts" and their modifications (Purcaru, 1981) play the main role in many of the successful earthquake predictions that have been made up to the present. The methods of discovering such phenomena are based on the analysis of the variation of the background seismicity in the period just before the main shock.
A difficulty here is the ambiguity in setting up a bound between the seismic source and its outer boundaries. Unlike the conventional approaches, the methodological problem of identifying structural formations just before the main event in Iran was solved by making use of time sequences of largest foreshocks with a low magnitude threshold that is lower by 3-4 than that of the shock examined.
The phenomena were searched for retrospectively by investigating the spatio-temporal evolution of the mentioned time sequences over a large area up to the earthquake of Jun 20, 1990. We analyzed a representative catalogue of events with the magnitude level 4.0 < M < 7.3 since the date of occurrence of the largest earthquake of 1962 with M = 7.2, the last one close to the event examined here. The examined territory covered more than 500 km in radius around its epicenter, based on the dimension of an earthquake process zone corresponding to M = 7.3.
Using the principle of hierarchy, main shocks were picked up from the catalogue by the method of successive elimination of foreshocks and aftershocks related with each of them. The total set of these main shocks in a wide temporal and spatial range were classified as foreshocks in a broad sense. Their time sequence took, in space, the shape of two separate orbital trajectories of distribution, one of them enclosed by the other.
The configuration of the first one is formed by a sequence of near-source foreshocks with M = 5.4-6.2 in the time period 1978-1983. This trajectory coincides with the boundary of the quiescence area, which 'includes

the deformations and the future source of rupturing. The second, outer orbital trajectory is composed of a sequence of distant large foreshocks with M = 5.6-7.0 over two most active time periods 1963-1976 and 1983-1989. It encircles the district of precursory seismic activity around the first trajectory and the zone of preparation for the coming main earthquake. This trajectory includes a number of effects of synchronized shocks, occurring at opposite locations far from each other. The Spitak earthquake of 1988 (M = 6.9) was also a part of the activity of this orbital trajectory.
A characteristic feature in our case is the absence of large foreshocks in the strict sense immediately before the main shock in its focal zone. The last such shock was observed in 1983 with M ~ 5.6. The closest in time is a large deep shock (M ≥ 6.0; h ~ 60 km), which took place on September 16, 1989 far from the source, in the Caspian Sea region inside the outer trajectory. This phenomenon, apparently, can be interpreted as the interaction of the aseismic district of South Caspia and the zone of preparation for the earthquake itself. The location of the precursory shock and the source of the large earthquake are genetically interrelated by the distribution within a single regional circular pattern that encloses the South Caspian block.
The above mentioned orbital trajectories of foreshocks in the form of the large and small circles present an untypical doughnut pattern over an extensive area. The outer district of this doughnut pattern is deformed, by the tectonic situation, restricted from the side of the Eurasian plate and of the aseismic rigid block in Eastern-Central Iran. The latter deformation, however, may also be due to an interference process of preparation for another large earthquake in the second, neighboring seismic gap. The location of the outer orbital trajectory coincides with the tectonic arc zones.
The algorithm for identifying such effects was also retrospectively tested for a number of situations before large earthquakes in Caucasus - Iran and China regions. In neighboring regions. In many of them we observed regular appearance of two or more orbital trajectories of sequences of interrelated large foreshocks, which are completed with the occurrence of the main shock in the center (Shemakha earthquake in 1902, M7.0; Tangshan, China earthquake in 1976, M7.8). Our findings indicate than middle-term prediction for 1976 Tangshan earthquake were the 1975 Heicheng earthquake.
Especially interesting are the dynamic spatio-temporal patterns found in relation with the 1895 Krasnovodsk earthquake with M = 8.2, the strongest in the examined period, which took place on the eastern coast of the Caspian Sea in Turkmenistan, because the characteristics of the sea level changes have also been revealed for this earthquake. Long-term changes in the sea level preceded this earthquake, in the shape of a hollow and a slow continuous oscillating rise over 40 years, and also there was a remarkable anomalous fall in the sea level over 5 years.
The observed positive anomalies in the temporal variation, superposed on the rising trend, are correlated with distant events with relatively smaller magnitudes (M = 6.0-6.9), whose spatial distribution presents an arc-shaped orbital trajectory of foreshocks in a broad sense. This arc encircles an extensive area of preparation for the main shock from the southwest and southeast, including the South Caspian and the West Turkmenistan Basins.
These results lead us to consider that the orbital trajectories of sequences of large foreshocks relative to the seismic source in Northern Iran might be a long-term precursor of the impending great event. Prediction of the source time might be based on a method of determining the gradient of the regularity of large foreshock occurrences.
The model that explains such phenomena before large earthquakes is based on the mechanism of formation of the doughnut pattern in the crust during the evolution process near the top of a fault or of formation of heterogeneity on its sides, It is also based on the differences in the character of simultaneous changes in the pore pressure that occurs due to the stress increase in the source itself and in the surrounding doughnut area. In this case, deformational hardnings and weakenings, related with compression and extension processes, can serve as a cause for fluidization.
On the base of complex of the geologic-geophysical and seismological approaches the study of structure and dynamics of the earthquakes focal zones there had been presented a map of dynamic seismic zonation and dynamic prediction of the earthquakes focal zones (Fig 3).

Figure 2. The dynamic spatio-temporal patters found in relation with the preparation of the local earthquake Krasnovodsk (1895) with M=8.2 and remote from the Caspian Sea Andaman-Sumatra earthquake with M=9.3

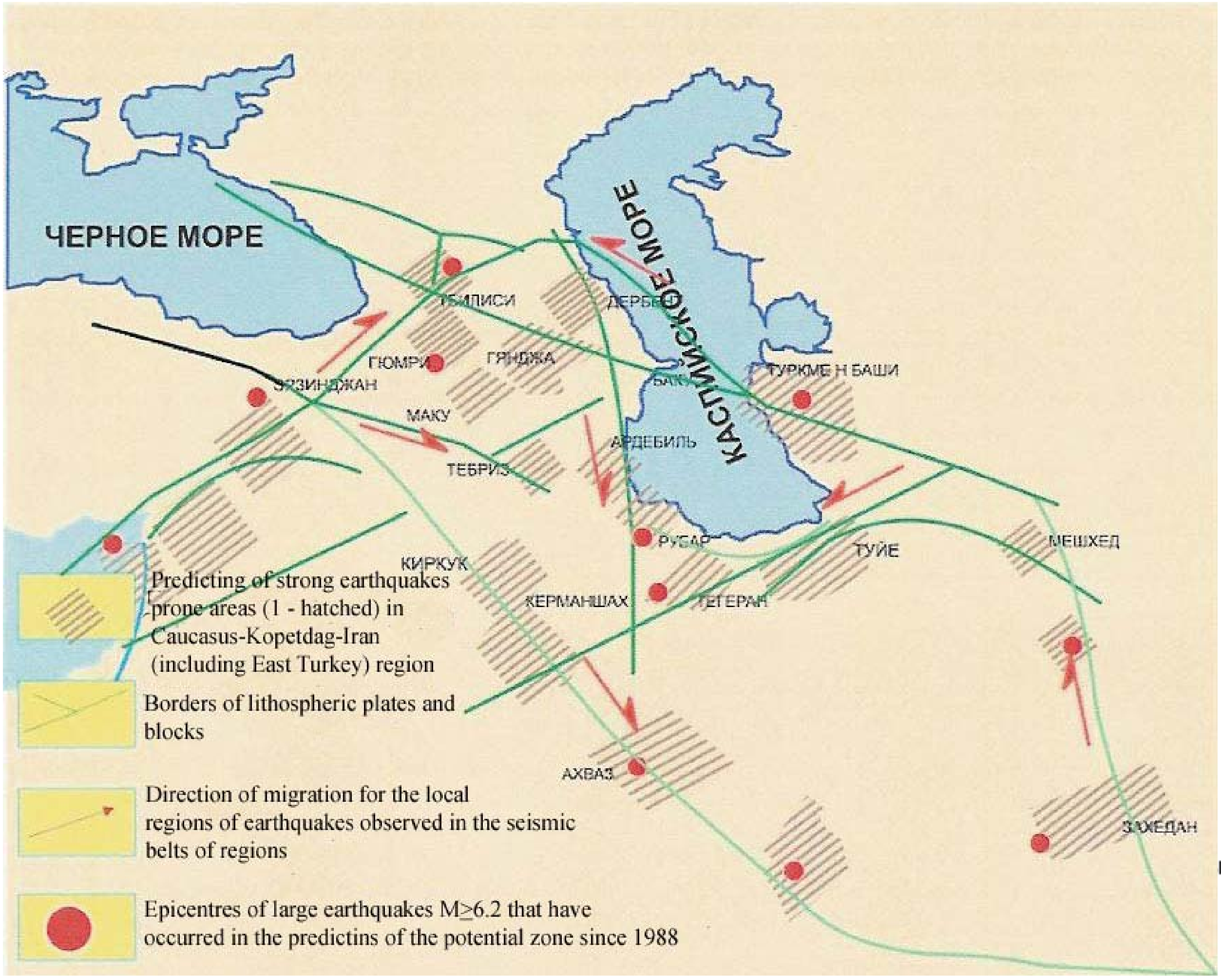

Figure 3. Results of predicting of strong earthquakes prone areas

4. Outline of earthquake detection systems for pipelines

The Strong Motion Instrumentation System applied for civil structures and nuclear power plants is also suitable for pipelines (O.B.Babazade, L.Grieseer and M.Wieland, 2004). Within 5 seconds, it provides a value of the impact of the earthquake to the pipeline. Figure 19 shows a typical pipeline section. The accelerometers of the Strong Motion Instrumentation shall be installed in hazardous seismic zones along the pipeline at a distance of 1 to 10 km depending on the seismic conditions. They are placed in small concrete vaults at zero ground level. With offshore pipelines, the accelerometers are attached directly to the pipeline.
As in the case of civil structures and nuclear power plants, the processing of the instrument signals consists of the following steps:

- Filtration in the range of approximately 0.1 to 10 Hz to eliminate the vibrations caused by other sources than earthquakes
- Fast Fourier Transformation, FFT, to determine the cyclic content of the signals
- Calculation of PGA and CAV.

For the assessment of PGA and CAV, the procedure outlined above for nuclear power plants is proposed to be applied. Specifically with regard to CAV, it is proposed to apply the standard threshold value for nuclear power plants of 0.16 g x sec because, according to the EPRI investigations, damage to structures can be excluded below that value.

The application of the standardized CAV value and calculation procedure provides the following advantages:

- The standardized calculation method of CAV eliminates re-investigations in each case.
- All suppliers of Strong Motion Instrumentation Systems can base on the same method of CAV calculation. This eliminates the necessity of rewriting the software in each case.

The Strong Motion Instrumentation outlined in the section above measures the seismic waves. However, it was explained that pipelines are more seriously affected by the secondary seismic effects, mainly the soil liquefaction with lateral spreading and the landslides. Instruments are available which measure the liquefaction and landslides in the soil. However, in order to detect the influence of these effects on pipelines, the direct measurement of the pipeline displacement is preferred. This can be done with the Distributed Temperature and Strain (DiTeSt) system of the company SMARTEC, Lugano-Manno, Switzerland. The system is based on fiber optic cables and laser light using an optical interaction measurement principle designated as stimulated Brillouin scattering (see Thevenaz, SPIE 5th Annual International Symposium on Smart Structures and Materials, San Diego USA, March 1998). The scattering arises from the interaction between the propagating light wave and thermally excited acoustic waves. Since this interaction depends on the strain state of the fibre, it is possible to detect and localize displacements. The interaction depends also on the temperature. Due to the fact that any leakage is connected with a temperature modification, leaking points in the pipeline can be detected by the same system. A recent application of the DiTeSt system is the monitoring of a buried, thirty years old gas pipeline, located near Rimini, Italy, in a landslide area. Three types of sensors were used, tapes, cords and temperature sensing cables. The tape is a sensing optical fibre integrated into a fibre-reinforced composite tape, thickness of 200 ja, attached directly to the pipeline. It provides the monitoring of the strain and the deformation of the pipeline.
It provides the monitoring of the strain and the deformation of the pipeline. The cord sensor consists of a sensing optical fibre integrated into a fibre reinforced plastic cord of 6 mm diameter. It was installed in the soil below the pipeline in order to monitor the strain changes in the soil. The measurements of the tape and the cord are correlated by the system in order to evaluate the strain transfer from the soil to the pipeline. The strain resolution of the system is 20 micro-strains with a spatial resolution of 1.5 m. The temperature sensing cable installed at the upper line of the pipeline monitors the temperatures, compensates the strain measurements for temperature and detects leakages. The resolution is 1°C with spatial resolution of 1.5 m.

As outlined above, the sensors are attached directly to the pipeline. However, at a new pipeline the applied pipe laying procedure might not allow the time delay required for this. In this case, the fibre optic sensor is attached to the SCADA tubing running along the pipeline. In case of a displacement of the pipeline by soil liquefaction or by landslides, it is assumed that the SCADA tubing follows the curvature of the pipeline.

The sensor signals are read and evaluated using a single DiTeSt analyzer. It needs approximately 60 seconds to evaluate the signals. Buried pipelines would undergo excessive shear stresses at fault movements. Therefore, the present state of the art is to arrange the pipeline at faults above ground in a zig-zag arrangement so as to allow extended movements. Due to the installation above ground, the deformation can be surveyed by GPS receivers.

5. IMPROVEMENT OF THE EARTHQUAKE SAFETY AND CONCLUSIONS

The pipeline design covers the normal pressure as well as other loads. As outlined above, the seismic waves of an earthquake are not expected to result in a pipeline fracture. However, in case of an extremely strong earthquake, there is a risk of a pipeline rupture due to soil liquefaction and landslides. Following the mechanism of formation, these effects have a certain time delay to the earthquake. This may be roughly 1 minute. The following considerations are made for a reference point arbitrarily selected at a distance of 30 km downstream of a pump station. Based on the evaluation of the Strong Motion Instrumentation, actions are taken, for example a full shutdown of the pipeline pumps in case of an extremely strong earthquake. This evaluation takes only 5 seconds. The shutdown of the pipeline pumps creates a pressure surge in the pipeline. According to the Joukowski formula the pressure surge propagation velocity in a steel pipeline of 1 m diameter completely filled with oil is roughly 1 km/s. Therefore, the shutdown of the pipeline will be felt 30 km downstream of the pumping station within 30 seconds. The stress in the pipeline starts to go down at that time. Due to the fact that in our scenario the landslide hits the pipeline 60 seconds after the earthquake, the additional stress caused by the landslide can be taken up by the pipeline. This procedure is designated as Pressure-Relief Before Break Principle. The pipeline displacement sensors in soil liquefaction and landslide areas and at seismic faults shall also issue a signal for intitiation of actions on the pipeline.

Although the above considerations are based on a certain scenario, it is evident that the risk of pipeline breaks can be reduced by this method. In this way, the earthquake safety of pipelines is improved.
Minimization of investment risk is feasible with the generation of normative maps of the dynamic seismic zoning for both the Caspian basin and the entire path of the oil pipeline. This must be done in accordance with international standards. It is possible to solve problems on seismic hazard assessment base on dynamic seismic zonation and earthquake prediction - methodologies. Such a long dynamic prediction for Caspian-Eastern-Turkey-Iran region based on systematic seismogeodynamic approach to investigation of focal zones of preparation main earthquake and on block modeling of seismokinematics of this region. At the same time the prediction not only the place strength of potential zones of the strongest earthquakes but also the periods of increased probability of the future mainshoke. This work also focuses on how an earthquake detection system would allow early detection by pipeline operation and how pipeline safety can the pressure – relief Before-Break principles.

The Earthquake Detection & Safety System provides the following advantages.

- The probability of a pipeline break in case of an extremely strong earthquake with soil liquefaction or landslide is lowered and, hence, the risk of huge investment losses is reduced.
- Due to the online determination of the earthquake impact on the pipeline, normal operation can continue in many cases. If the measured data allow, a partial flow of approximately 50% is maintained. A full shut down is initiated if absolutely required only. Therefore economic operational losses caused by earthquakes are minimized.
- The ecological risk connected with the pipeline is reduced.

In this way, the economic value of a pipeline is maximized and the ecological risk is reduced by the Earthquake Detection & Safety System.

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