8th World Seminar on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structure
Yerevan, Armenia, October 6-10, 2003

THE EC-FUNDED PROJECT "INDEPTH"

Fabrizio Gatti[1], Luis Dorfmann[2], Alessandro Poggianti[3], Maria Gabriella Castellano[4], Joaquin Marti[5], Paul Summers[6], Dimitris Karabalis[7], Nikolaos Skandalis[8], Heiko Silbe[9]

1- Enel.Hydro/BU ISMES, Seriate (BG), Italy -E-mail: gatti.fabriziog@enel.it
2- IKI, Vienna, Austria – E-mail: dorfmann@mail.boku.ac.at
3 -ENEA, Bologna, Italy - E-mail: alessandro.poggianti@bologna.enea.it
4 -FIP Industriale S.p.A., Selvazzano Dentro (PD), Italy-E-mail: castellano.fip@fip-group.it
5 - PRINCIPIA Ingegnieros Consultores S.A., Madrid, Spain, -E-mail: marti@principia.es
6 - MMI Engineering Ltd,, Warrington, UK, E-mail: psummers@mmiengineering.com
7 - Univ. of Patras, Department of Civil Engineering, Patras, Greece, E-mail: karabali@upatras.gr
8 – Hellenic Petroleum, Aspropyrgos Refin., Aspropyrgos,Greece,E-mail: nskandalis@hellenic-petroleum.gr
9 - IWKA Balg- und Kompensatoren GmbH, Stutensee, Germany, E-mail: silbe@iwk.de

ABSTRACT

The Project INDEPTH (Development of INnovative DEvices for Seismic Protection of PeTrocHemical Facilities), supported by the Environment and Sustainable Development Programme of the European Commission Research Directorate General (Contract EVG1-CT-2002-00065), has the objective to develop and apply innovative seismic isolation and/or dissipation devices for critical structures at petrochemical facilities, such as cylindrical/spherical tanks, thereby reducing the seismic risk at such facilities in highly-seismic areas, where a limited number of such applications exists, apart very few in LNG tanks. It is known, however, that a seismically isolated structure subjected to an earthquake can experience large displacements, potentially overstressing the attached piping. Moreover, isolation systems are generally designed for given value of supported mass and their performance can be non-optimal when the mass is varying, as in case of tanks, where the level of liquid frequently changes during day-to-day operations.

In the framework of the Project, new devices are developing to solve specific issues such as the lack of isolation systems, where performance is independent of the mass associated with the liquid level inside tanks, the lack of low-cost, light-weight new isolators and the "compensation" for high displacements associated with an isolated structure in order to avoid piping overstress.

The paper describes the general problem of seismic risk at petrochemical facilities, the approach adopted for the development of INDEPTH Project, the first results (selected structures, seismic hazard, numerical models developed) and the expected achievements. The Project started in Sept., 1st, 2002 , has an overall duration of three years and, at the moment of the Seminar, is at the end of its 1st Year.

1. PROBLEM AND ITS SIGNIFICANCE

It is well known that some parts of Europe are in areas of high seismic risk, and within this area there are numerous refineries and other petrochemical/industrial facilities.
The motivation for the project is to increase the seismic performance reliability of such facilities, both existing and future, in the face of high earthquake risk, through the development of new and innovative devices and techniques. Concern for society, quality of life of surrounding communities and impact on the environment, forces policy makers to assess the risk of hazardous material releases from refineries and petrochemical facilities during earthquakes. In fact, a major seismic event in an industrialised area could damage (and has damaged in the past) process equipment, storage facilities and transfer (or lifeline) systems. The start of fires and the release of airborne toxic gases and/or volatile liquids may obstruct post-earthquake rescue operations and have major social and economic consequences. An example in case is the initiation of multiple fires at the Tupras oil refinery and loss of production after the Izmit earthquake in Turkey [1, 2, 3, 4].
The concerns relevant to the abovementioned highlighted problems are relevant to the increment of seismic reliability of existing and future facilities, the assessment of risk (i.e. casualties, releases of hazardous materials, damage to structures, equipment and facilities) and the support to post-event rescue operations (risk of fires, release of toxic fluids, etc.).
INDEPTH Project is mainly focussed on the first item, i.e. to increment the seismic reliability of existing and future facilities, through the development of innovatives anti-seismic devices.

2. PROPOSED APPROACH

The approach of the Project to the problem is articulated on the following main topics:

- selection of critical structures from walkthroughs performed at Aspropyrgos refinery, Greece and Huelva LNG facility, Spain; selection of main design parameters of the devices
- definition of site-specific and generic seismic hazard
- design and manufacturing of the devices
- numerical analyses to confirm the design parameters vs. the expected dynamic behaviour of the devices, identification of specific fluid-soil-structure-interaction (FSSI) problems and experimental validation through shaking table tests
- quantification of technical/economical/safety benefits with respect to the conventional state-of-the-art measures presently adopted and potential application to retrofitting.

A selection of the most vulnerable structures found in petrochemical facilities has been made on the basis of the experience of the team. These structures are LNG and critical product storage tanks (such as firewater tanks), spherical storage vessels (often containing ammonia or LPG).
For each of these components, an optimal solution (in terms of technical effectiveness and economic feasibility) capable of reducing the seismic vulnerability and enhancing the performance reliability is to be developed in this project. In particular, for each structure, a seismic isolation and/or energy dissipation system will be selected as an alternative (and an improvement) over the more traditional seismic design or retrofit concepts. The project objectives will be pursued by:

- Development of new concept seismic isolators and flexible joints for accompanying interconnected piping, conceived by taking into account the specific needs of variable-mass cylindrical tanks/spheres, recognized as some of the most critical components (for their potentially dangerous contents and by their inherent seismic vulnerability) in a petrochemical facility.
- Use of updated state-of-the-art analytical techniques to compute and measure the effects of fluid-soil-structure interaction (FSSI) on the seismic behaviour of structures in both their existing configuration and with the proposed new isolation/energy dissipating devices, subject to the appropriate performance requirements.
- Quantification of the technical and economic benefits of such devices, including consideration of the need for protection from fire and chemical attack due to the highly aggressive and corrosive operating environments.
- Preparation of guidelines for selection of proper isolation and/or energy dissipating devices.

The active participation of end-users in the formulation of the main objectives assures that the scientific/technological goals will be relevant to industry requirements and focus on problem-solving research. Furthermore, to ensure that real operational issues associated with actual industrial plants are addressed, candidate structures will be determined following a limited vulnerability screening of selected portions of the Aspropyrgos Refinery and the Huelva LNG facility, located in highly seismic areas of Greece and Spain, respectively, following input from facility personnel.

In the framework of the Project, new devices are developing to solve specific issues such as the lack of isolation systems, where performance is independent of the mass associated with the liquid level inside tanks, the lack of low-cost, light-weight new isolators and the “compensation” for high displacements associated with an isolated structure in order to avoid piping overstress.

3. THE SELECTED STRUCTURES

Three types of structures found in petrochemical facilities have been selected as examples for the application of isolation devices in this project:

- Above grade LNG storage tanks.
- Above grade vertical storage tanks containing liquid product or firewater.
- Spheres containing pressurised (and possibly refrigerated) liquid product.

Each of these structures represents a different set of economic and technical challenges when applying base isolation devices.

Large LNG storage tanks of the order of 160,000 m^3 volume are found in LNG export liquefaction and import regasification facilities (the latter being more relevant to risk of seismic loads in Europe due to demand for gas). The LNG tank stores natural gas in a liquefied state at a temperature of -168°C, which represents a considerable quantity of stored chemical energy that would be released should a failure due to seiami event result in the liquefied gas coming in contact with atmospheric oxygen, with a significant risks to the surrounding population, should a containment failure occur because of an earthquake. LNG tank designs are, for the most part, designed as above ground structures with concentric steel inner (containing the liquefied gas) and outer reinforced/prestressed concrete shells. Design of the tank to withstand seismic loads presents specific issues, particularly anchorage of the inner tank to the outer tank structure.

At present, there are four sites with base-isolated LNG tanks. In all cases, the use of isolation units was expensive and had significant impact on construction schedules. The challenges therefore for applying base isolation to LNG tanks within the INDEPTH project is to develop an economic isolator unit that can be used for the expected range of tank sizes in Europe, that can be installed with minimum impact on construction schedule, and that can accommodate the unique variability of the mass of stored product (from full to near empty).

Conventional product storage (containing crude oil, ethylene, benzene and other aromatics) and firewater tanks containing liquid, up to over 100,000 m^3 in volume, are the most common type of storage unit in petrochemical facilities. Containment of these products (harmfully to the environment and extremely flammable)during a seismic event is therefore desirable.

Their typical construction costs are relatively low (unless anchorage is required) and consequently, base isolators would need to be economic to be viable. For anchored tanks, the cost of isolators can be offset against the cost to include anchorage in the design, and the cost of modifications to the tank foundation system. It is in this application that the INDEPTH project will focus on (economic) fibre reinforced rubber bearing isolators.

Spheres containing liquid product under pressure also represent a significant hazard should a failure and subsequent loss of product occur. A typical sphere consists of a near spherical pressure vessel, supported on between eight and twelve legs, braced to act as the primary lateral force resisting system of the structure.

In addition to its variable mass, a key aspect of isolating spheres will be to ensure that there is minimal differential motion between the base of each leg. As with other structures, the economic inclusion of isolators will require the cost of the isolators and associated design modifications (including flexible piping and connections) to be offset by reductions in the design and construction costs of traditional spheres and a demonstrable reduction in seismic vulnerability during large earthquakes (and beyond design basis conditions).

Finally, a major challenge for designing isolator units for all three of the selected structures is that the mass of contained fluid will vary throughout operational life. Consequently, the base isolation units must also be able to cater for variable mass in their design. Further, the cost of using isolation will need to include any additional cost in providing flexibility in the piping and other connections that span between the structures and the first adjacent fixed pipe support or other point of fixity (such as a containment wall through which the piping penetrates).

Six specific candidate structures have been selected in the sites of Huelva and Aspropyrgos for the analysis:

- Two LNG storage tanks (Figures 1 and 2) with the following main characteristics:
    - Capacity 60000 m^3 and 100000 m^3
    - Outer tank diameter: 49,41 m and 67 m
    - Aspect ratio (Height/diameter): 0,81 and 0,56

Figure 1: Huelva LNG plant: 60000 m^3

Figure 2: Huelva LNG plant: 100000 m^3

- Three liquid storage tanks(Figures 3, 4 and 5)with the following main characteristics, which cover a quite wide range of different type of content and aspect ratios (T729 was not in Aspropyrgos, but in another site, inspected before the start of the Project):

Tank identifier code	P8803	P5151	T729
content	ATM Residue	Demin Water	Lube Oil
Capacity (m^3)	67600	8557	755
Mean diameter	66.44	24.4	8.24
Aspect ratio	0,29	0,75	1,75

Figure 3: Tank P8803

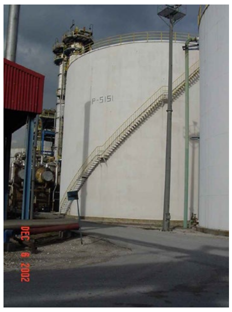


Figure 4: Tank P5151

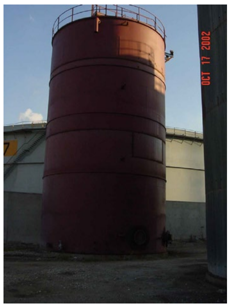
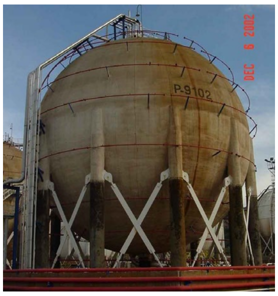


Figure 5: Tank T729

- One spherical tank containing refrigerated polypropylene with the following main characteristics:
    - Capacity 4200 m^3
    - Sphere diameter: 19,6 m
    - Number of supporting columns: 11



5. THE SEISMIC HAZARD

Amongst the potential earthquake related hazards (the seismic hazard) that may affect the structures, equipment and piping at a petrochemical facility, the ground shaking is responsible of the most serious and widespread damage, since other hazards (ground failure caused by the rupture of a fault and by liquefaction and/or landslides and coastal inundation caused by seiches, tsunamis or tidal waves) are normally guarded against by careful site selection.
For most petrochemical facilities, evaluation of seismic hazard is governed by codes, standards (national and international) and design norms that are relevant to location of a specific facility, requiring seismic loads to be considered for a single event, prescribed by the probability of a given earthquake occurring within a specific time period.
An exception to this is seismic loading at LNG facilities, where a dual criteria approach (from the nuclear industry) is mandated (CEN, 1994 and NFPA, 2001):

- Operating Basis Earthquake (OBE), intended to guarantee continued operation (or limited downtime/economic loss) at a lower level event; elastic or near-elastic design rules are used and the return period adopted is 475 years, cooresponding to a 10% probability of exceedance in a lifetime of 50 years
- Safe Shutdown Earthquake (SSE), intended to afford the general public and environment a level of safety should an extreme earthquake occur; design rules are fully non-linear, a complete loss of function, even permanent, is allowable (except major collapses or major releases of hazardous materials) and the return period is 10,000 years (reduced to 5,000 years by the latest version of NFPA 59A).

The seismic hazard is generally evaluated using a probabilistic approach, taking into account activity rates, existing geological and tectonic data and attenuation laws in order to calculate the effects at the site. Several approaches exists from the traditional procedure described in [8] to the more innovative outlined in [6] and [7], used also to define the seismic hazard at a number of LNG facilities ([5]). For calculation purposes the seismic hazard is defined using response spectrum or artificial time histories generated from response spectrum.
In the development of the INDEPTH Project, specific seismic hazard assessments are avalailable to perform accurate analyses on the tanks identified as candidate structures in the two reference sites (the Huelva LNG plant in Spain and the Aspropyrgos refinery in Greece). Nevertheless, as many investigations have to be carried out in a generic fashion, so that the results might be applicable to other locations in Europe and, indeed, elsewhere in the world, a generic description of the hazard at a site, in terms of spectral shape and reference peak ground acceleration, has been adopted, allowing studying the acceleration levels at which the various design solutions are unfeasible, attractive, required, etc..

The spectral shapes (as SB, SC and SD) adopted, see Fig. 6, are those that EC8-draft (CEN, 2002) recommends for soil types B, C and D and type 1 earthquakes (magnitude M_s>5,5) and S=1: the spectral shape for the vertical motion can be obtained multiplying by 0.7 the shape obtained for the horizontal motion. The reference acceleration a_g will be taken as a continuously varying parameter, descriptive of the hazard level at the site.
Finally, some analyses may have to be carried out in the time domain. To make them possible, two accelerograms have been generated for each of the three spectral shapes adopted: one having a duration of 20 s and the second one during 40 s. An example of these accelerograms is presented in Figure 7 together with the corresponding spectra. The accelerograms will be scaled up and down, in proportion with the reference peak ground acceleration, in order to avoid introducing additional variables in the generic analyses.

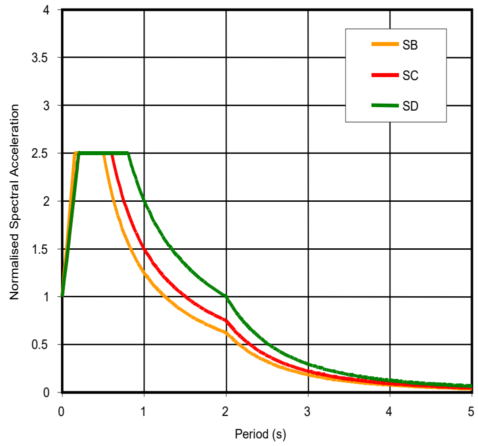


Figure 6: Recommended Spectral Shapes in Terms of Period

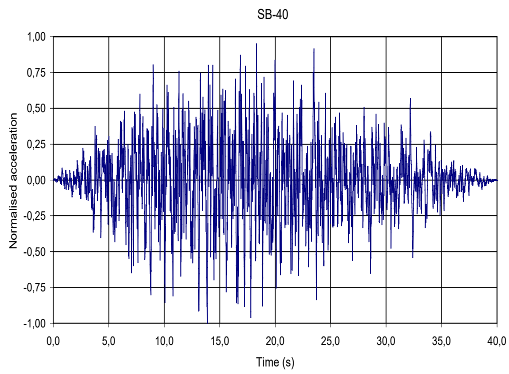
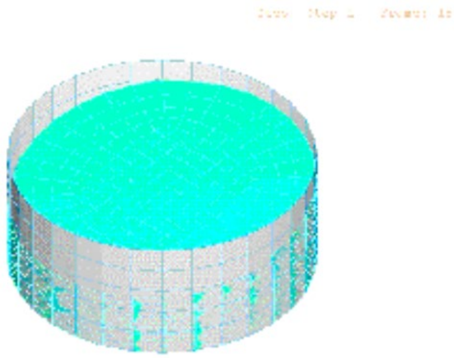


Figure 7: Normalized acceleration time history (soil B, 40 seconds)

5. THE NUMERICAL ANALYSES

The numerical analyses are in progress, to support the development of the new anti-seismic devices. The analyses take into account different topics such as the non-linear behaviour of isolation devices, the effects of sloshing motion at different filling levels, the soil-structure interaction and the fluid-structure interaction; they are developed on different level of complexity, starting from simple classical Housner models to the most sophisticated codes, in order to supply design procedure tuned on the candidate structures chosen. As an example, the following sketch illustrates the effect of sloshing of the content inside the P5151 tank.



6. THE EXPERIMENTAL VALIDATION

The experimental validation foresees a shaking table testing phase, particularly focussed on the experimental verifications of the effectiveness of the assembly "devices+mockups". The experimental equipment, owned by one of the partners (Enel.Hydro/ISMES), is a 4 m × 4 m triaxial shaking table (Figure 8), able to test up to 300 kN specimens, with a maximum overturning moment up to 300 kNm, with 5 g's of maximum peak acceleration in horizontal/vertical directions and ±100 mm displacement.

Figure 8 The 6-DOF MASTER shaking table at Enel.Hydro/ISMES premises (Seriate, BG, Italy)

Two physical mockups are foreseen:

- Cylindrical mock up
- Spherical mock up

The spherical mock up will be equipped with no more than 4 ÷ 6 legs of limited height, to fulfill the maximum overturning moment limitations. Currently, the design of the mockup is in progress.

The mock ups will be tested both with and without the isolation devices developed in the framework of the Project, with different level of fluid inside, by measuring accelerations, displacements and strains with appropriate sensors.

7. THE EXPECTED ACHIEVEMENTS

The expected results and products of the Project are full scale demonstrators of the devices developed, an integrated procedure for FSSI problems solving, the assessment of the benefits with respect to the conventional retrofitting techniques and design guidelines: in fact, considering that the devices to be developed are completely new, their use in a petrochemical environment will have to be strongly supported by a quantification of the technical and economical benefits, comparing them with the conventional state-of-the art measures presently adopted in such type of plants, focussing the aspect of retrofitting, obtained through conventional methods and innovative devices. A particular emphasis will be devoted to the safety issue, quantifying this increase with respect to the conventional methods. A specific workpackage of the Project is devoted to this topic. Moreover one of the main objective of INDEPTH is to promote the seismic isolation application in the context of the petrochemical facilities.

REFERENCES

[1] Eguchi, R.T., Tierney, K.J. and Antonoplis R.A. (1988), "*An Assessment of the Risk of Hazardous Materials Release during Earthquake – The Impact on Surrounding Communities*." Proc. of 9th WCEE, World Conference on Earthquake Engineering, 1988. Vol. VII, pp.545-550.

[2] Lindell, M.K. and Perry, R.W. (1998), "*Earthquake Impacts and Hazard Adjustment by Acutely Hazardous Materials Facilities Following the Northridge Earthquake*." Earthquake Spectra, Vol. 14, No. 2, pp. 285-290.

[3] Bruneau, M., (1999) "*Structural Damage: Kocaeli, Turkey Earthquake, August 17th, 1999*". Report from the Multidisciplinary Center for Earthquake Engineering Research, University of Buffalo, NY.

[4] Rahnama, M. and Morrow, G., "*Performance of Industrial Facilities in the August 17, 1999 Izmit Earthquake*", 12th WCEE, World Conference on Earthquake Engineering, Auckland, New Zealand, 2000.

[5] Crespo, M.J. and Martí, J., 2002, '*The Use of a Zoneless Method in Four LNG Sites in Spain*', 12th European Conference on Earthquake Engineering, London, September

[6] Woo, G., 1995, '*A Comparative Assessment of Zoneless Models of Seismic Hazard'*, 5th International Conference on Seismic Zonation', Vol. I.

[7] Woo, G. 1996, '*Kernel Estimation Methods of Seismic Hazard Area Modelling*', Bulletin of the Seismological Society of America, Vol. 86, No. 2, April, pp. 353-362

[8] Cornell, C.A., 1968, '*Engineering Seismic Risk Analysis'*, Bulletin of the SeismologicalSociety of America, Vol. 58, pp. 1583-1606

ACKOWLEDGEMENTS

INDEPTH (EVG1-CT-2002-00065) is supported by the *Environment and Sustainable Development Program* of the European Commission, Research Directorate General.