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Seismic retrofit of Chirag 1 offshore platform

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Abstract

This paper presents an overview of the application of seismic isolation to a fixed-base offshore platform. The technology, already widely used to protect civil engineering structures like bridges, buildings and nuclear or industrial plants, has also found valid application in the field of offshore oilrigs.
In fact, more than a year has transpired since the Chirag 1 offshore oil platform located in the Caspian Sea, the first such seismically isolated offshore structure, has been operational.
The seismic protection of this type of structures represents a further step toward the enhancement of structural safety under particularly adverse conditions, which can accrue important results in terms of preventing environmental disasters with associated human and economic losses.

1 Introduction

The study of a structure particularly prone to seismic attack requires certain basic considerations that must be taken into account in terms of the nature of the phenomenon itself, which must be followed by some strategic choices and the latter depend on the type of structure, the seismicity and geological nature of the site, as well as building codes currently in force and other incidental parameters.
Unlike other forces acting upon the structure, the seismic phenomenon is energetic. The energy transferred into the structure during an earthquake is partly stored and partly dissipated: the greater the amount of energy undergoing dissipation, the lesser the energy stored as kinetic and elastic potential energy.
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As it is desirable not to interrupt, either temporarily or permanently, the function of the structure due to structural damages, it was thought to install devices that can localize the dissipative effect.

These devices, located at the superstructure-substructure interface, are commonly referred to as seismic isolators inasmuch as their function is that of "isolating" the deck from the substructure and thus, from the ground. Their behavior, whenever a certain load threshold is exceeded, is hysteretic and thus dissipative in nature. In fact, said isolators are equipped with internal steel elements so designed as to furnish stable behavior even under plastic deformation.

A fundamental tenet of this structural type is for the devices to be highly dissipative in addition to furnishing a certain amount of flexibility.

In the case illustrated below, the Chirag 1 platform seismic retrofit, there were a number of conditions binding the project, both in terms of the maximum horizontal force transmissible to the substructure as well as maximum admissible displacement of the platform equipment.

Obviously, either exceeding the maximum relative displacement limit between deck and substructure or the maximum admissible horizontal force could cause human, economic and environmental losses that would be inadmissible.

2 Description of the Existing Chirag 1 Platform

The Chirag 1 platform was built by the former Soviet oil board in the homonymous oil reserves located approximately 120 km offshore the coastal city of Baku in Azerbaijan and remained operational until Azerbaijan declared its independence from the Soviet Union.

The Chirag 1 platform erected in approximately 120 m of water along the Apsheron Sill in the Caspian Sea, consists of two 10-pile, back-to-back jackets that were designed to support 19 topsides drilling and production modules weighing approximately 12500 tonnes. Original platform design production rates were 6000 tonnes/day (46000 bpd) of oil and 800000 scm/day (23 MMscfd) of gas.

The drilling jacket was launched in 1991, and piling was completed on the production jacket in early 1993. Bay heights range from 12 m at the top of the jacket to 18 m near the bottom; the bottom bay height is 6 m. The jackets were fabricated using the nodal method of construction; the brace stub-to-leg welds are one sided.

There is no evidence of either increased steel wall thickness or steel with improved through-thickness properties in the jacket legs or in the truss K-joints.

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In-fill braces are butt-welded (with an internal back-up bar) to the stubs at one end, and fit with an external sleeve splice at the other end.

All truss braces below Elevation -29 m have internal ring-stiffeners to prevent hydrostatic collapse.

Each jacket is supported by 10 piles that vary in design penetration between 110 and 150 m; actual penetrations have been determined to range from 102 to 128 m. The combined weight of the jacket and piles is estimated to be 5400 tonnes.

The jackets are installed such that the top level of horizontal framing is at El. +10 m. The piles extend through the jacket legs and are capped with steel plates. There are eight lower level modules (top-of-steel cellar deck elevation of +12.6 m), of which seven have been set and partially welded directly on the pile caps; a single pile supports as many as four modules. Shim plates have been used between the pile caps and the modules to compensate for differences in the pile head elevations. These eight units include 2 drilling, 4 production, 1 cementing, and 1 generator/control modules. The quarters and helideck modules are installed above the cementing module.

3 Determination of the Retrofit Solution

A consortium (AIOC) comprising 12 partners from different nations (United States, Great Britain, Union of Independent States, Azerbaijan, etc.) secured the concession to exploit oil reserves and, in December 1994 established an integrated project team to evaluate the partially completed Chirag 1 platform in an early oil development scheme, as well as to develop preliminary engineering designs for said scheme. Even though of recent vintage construction, the Chirag 1 platform was not designed to withstand either seismic loads or high intensity storm events.

The preliminary approach of the AIOC team to the Chirag 1 platform structural assessment was to collect and input site-specific information into a three dimensional, fully non-linear structure and foundation analysis model. Site-specific information was collected by two soil borings, underwater survey and an air diving inspection.

ISEC, a highly respected consultant in the field of earthquake analysis, was retained to assess the integrity of the jacket design by generating a three dimensional, fully non-linear structure and foundation model using their in-house programme KARMA. The objective was to find the probability of catastrophic seismic and wave loads that will take the structure to failure. It is lateral loading of the piles during an earthquake that is the critical structural failure mode. Preliminary results indicated that the pile foundations could not sustain the level of loads associated with 1000-year return period earthquakes, the API and the recommended ISO target level earthquake which a structure is intended to resist. The Chirag 1 platform structural assessment, which included static form, non-linear pushover (static ultimate strength), and non-linear timehistory analyses, identified the weak link in the platform structure as the soil-foundation system. In order to achieve the desired level of platform reliability, either the structural system had to be strengthened or the loads developed within the system had to be reduced. The piles had already been internally strengthened with inserts and concrete fill. Gravel dumping was not considered effective since analyses indicated that a stronger soil system did not significantly affect overall strength.

Foundation strengthening systems, such as additional skirt piles to be installed *in-situ*, additional outrigger structures, etc., were eliminated as either too costly or schedule-intensive. The alternative to strengthening was to alter the dynamic response of the platform. The exposure of the twenty pile caps offered an ideal location for the installation of a Seismic Isolation System - a system that could be easily integrated into the planned platform topsides reinstallation. A bi-linear element that represented the Seismic Isolation System was added to the structural model, and through an iterative process of balancing relative deflections and load generation, along with consideration of various manufacturers' capabilities, a device with acceptable characteristics was developed that met the stringent criteria. The FIP isolator device was chosen due to its separation or vertical and lateral/dissipation capabilities, performance characteristics, use of reliable materials, durability, negligible maintenance, adaptability into the existing structural system, and the comprehensive in-house engineering, manufacturing, and testing capabilities offered by FIP. Selection of base isolation as the retrofit solution offered an analytically defensible, economic, and schedule-sensitive solution to the Chirag 1 Platform refurbishment project.

The scope of this presentation is to illustrate the Seismic Protection System specifically conceived for the Chirag 1 Platform.

Therefore, only the main operational phases of the complex retrofit project will be listed:

- remove existing modules, transport them to shore and refurbish as required;
- modify pile caps to ease the installation of the isolators;
- install the seismic isolation system;
- manufacture and install the Module Support Frame (MSF);
- re-install the refurbished modules.

4 The Seismic Isolation System

The Seismic Isolation System for the Chirag 1 Oil Platform consists of 20 devices, one for each pile, sub-divided into two types, with different vertical capacities (respectively 12000 and 22000 kN) but identical characteristics on the horizontal plane.

The General Requirements stated the following:

"The Seismic Isolator to be provided under this specification shall be comprised of a spherical PTFE multi-directional sliding bearing equipped with steel hysteretic dampers. The isolator shall be configured such that its lateral energy dissipation capability is independent from the effects of vertical loading. The sliding plane shall be located on the top side of the isolator, with the top plate of the device also serving as the backing plate of the sliding element."

It is known that a Seismic Isolator must be capable of ensuring the following four functions: transmit vertical loads, provide lateral flexibility, provide restoring force and provide energy dissipation.

FIP isolators are so conceived as to maintain - *within the isolator* - a clear separation between the device which transmits vertical loads and provides lateral flexibility (first two functions) and the device that takes care of the horizontal actions (remaining two functions).

In the case of the Chirag 1 isolators, vertical loads are transmitted through traditional PTFE spherical sliding bearings of the "free sliding" type - thus providing also lateral flexibility - and the other two isolator functions are provided through steel hysteretic dissipators of in such particular an arrangement as to allow the accommodation of relatively large displacements.

The FIP design conception of seismic isolators accrues several advantages, which can be summarised as follows:

a. vertical and horizontal actions can be dealt with separately, through important simplifications from a design and constructive standpoint;
b. reciprocal influences of the two types of loads are eliminated, and particularly the incidental damage of one or more hysteretic devices does not lead to bearing failure so the platform can remain operational;
c. any defect in one or more steel hysteretic elements does not jeopardise isolator functioning in that such dissipative elements work in parallel; in addition to modularity, this arrangement also provides redundancy and thus all the advantages this feature entails in terms of safety and reliability.
d. vertical loads are always centred at the desired point independent of the amount of displacement incurred.

The last characteristic is particularly appreciated in the case of oil platform piles inasmuch as they are very slender and thus sensitive to eccentricities. It is important to note that, in general, FIP steel hysteretic dissipators have the capacity to resist several design-level earthquakes (usually more than five).

In the specific case of the Chirag 1 Platform, due to API regulations, the design level earthquake corresponds to the MCE.

Nonetheless, the Chirag 1 Platform designer opted to specify an additional safety system for cases exceeding the MCE level. With the occurrence of such an extremely unlikely event, and though accepting some structural damage, it was also required that platform collapse as well as any major environmental damage be avoided.

To fulfil this requirement, the seismic isolators have been equipped with a second line of defence consisting of an additional system of steel hysteretic dampers (a so-called *ultimate system*) that is activated beyond MCE design displacement.

Lastly, in order to avoid subjecting steel hysteretic dissipators to service loads (wave and wind actions) which can induce fatigue phenomena in the elements themselves, the Chirag 1 Isolation System has been equipped with sacrificial restraints, which in fact render the isolators temporarily fixed. Said sacrificial restraints fail at the occurrence of a design-level earthquake and the base isolation system is automatically activated. In this manner, the platform behaves as a traditional structure during normal service and accrues full seismic protection at the occurrence of an earthquake.

5 Testing

This section presents the results of tests conducted on a Seismic Isolator having a 22000 kN vertical capacity (see Figure 1). The test was carried out by FIP Industriale's testing facility and experienced personnel at Selvazzano, Padova (Italy) and supervised by Mr David Grimm P.E. of the AIOC Houston Integrated Project Team. Testing on the seismic isolation bearing was completed during the week of March 10, 1997.

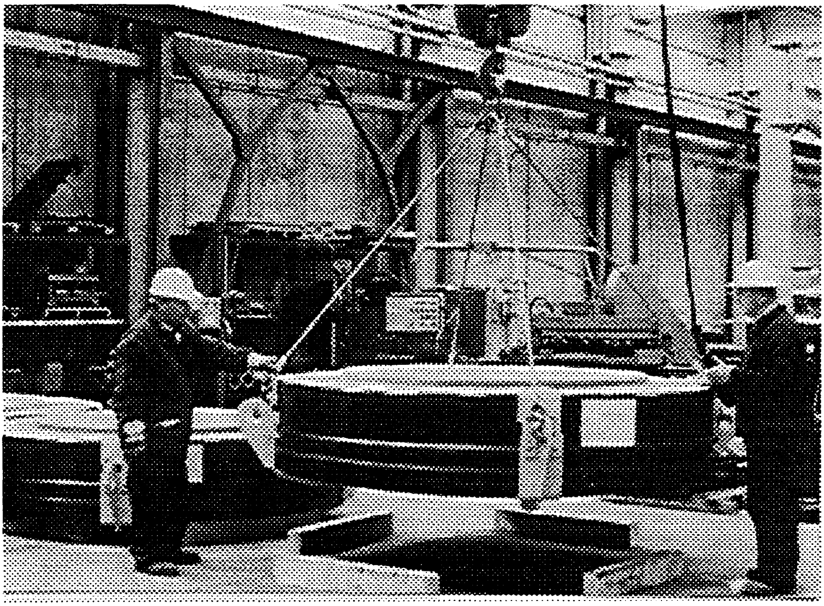

Figure 1. Isolator with protective sheathing and lifting padeyes ready for shipment

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5.1 Testing Program

The project specification (AIOC SES 2.B.900, 1996) provided for a series of tests, some to be conducted on prototype elements and some on the completed prototype isolator. These were carried out as follows:

5.1.1 Prototype Elements

- Friction test on PTFE specimens
- Hysteretic test on damper elements
- Service load break-away test

5.1.2 Completed Prototype Isolator

- Vertical load test
- Hysteretic behaviour test
- Restraint limit test
- Life limit test

5.2 Testing Procedure and Results

The paragraphs that follow report the results of each test as well as the procedure followed.

5.2.1 Friction Test

The objective of the test was to provide a correction factor for the effect of velocity on the coefficient of friction in the Lateral Load Test of the complete isolator prototype.

The displacement tests were conducted on two lubricated, dimpled PTFE discs in contact with stainless steel sliding elements (as in the isolators). During the test, the samples were subjected to a contact pressure equal to that produced in the isolators by the maximum load. The results shown below were taken as the mean value of those read during the 10 cycles. The symbols μ_{ref} (v=1.67 mm/s) and μ_{sis} (v=125 mm/s) represent, respectively, the friction coefficient values at *quasi-static* and *seismic* velocities.

Friction Coefficient	μ_{ref}	μ_{sis}
σ = 44,5 MPa	**0,0021**	**0,0060**

The friction coefficient values obtained can be considered to correct the hysteretic loop for the increase in friction resistance due to the effect of velocity.

5.2.2 Hysteretic Element Test

The objective of this series of tests was to determine the hysteretic loop of the dissipative elements.

Each test was conducted upon a dissipating module (1/32 of the total), deformed from the initial position by ± 150 mm, at a velocity of 2.5 mm/s in accordance with the Engineer specifications. The test was repeated on two series of dissipating elements until the elements failed. The load values recorded during the test were properly constant, both during compression and extension. The first 15 cycles are all comprised within an interval equal to 10% of maximum load. The failure always occurred after the 18th cycle.

5.3 Service Load Break-Away Test on Sacrificial Restraints

The objective of this test was to verify the failure force of the Sacrificial Restraints. The load was applied in a constant manner until shear failure occurred. The maximum load was 2974 kN corresponding to 1487 kN per specimen and was almost equal to the required value (1500 kN ± 20%). Deformation was approximately 4 mm at maximum load and 5 mm at complete failure. Such values met the acceptance criteria.

5.4 Complete Prototype Isolator

5.4.1 Vertical Load Test

The objective of the Vertical Load Test was to verify the load capacity of the seismic isolator under a vertical load of 27500 kN equal to the maximum expected load increased by 25% in the presence of maximum rotation.
The recorded deflection met the acceptance criteria.

5.5 Lateral Load Test

The objective of the lateral load test was to verify the isolator behaviour when subjected to a lateral displacement (reference velocity =1.67 mm/s). During the course of the tests, all lateral load-displacement curves were traced correcting for the increase in friction resistance due to the effect of velocity using the formula: Corrected Value = Reading $+ (- 2\ P_0\ \mu_{ref} + P_0\ \mu_{sis})$, in which the values for the friction coefficient are those previously reported (§ 5.2.1).

5.5.1 Hysteretic Behaviour test

The objective of this test was to verify the hysteretic behaviour of the isolator when subjected to the MCE design lateral displacement.
The hysteresis loops plotted for all the required 15 load cycles conducted at a ± 300 mm deformation and obtained at different orientations (0°, 45°, 90° and 135°) showed to met the acceptance criteria tolerances being within 10% of the design characteristic law.

5.5.2 Restraint Limit Test

The objective of this test was to verify the ultimate behaviour of the isolator when the MCE design displacement is exceeded.

This phase of the testing was conducted increasing the stroke to ± 350 mm. The graph in Figure 2 shows the lateral load *vs* displacement curve for two cycles (only one was required). As it can be appreciated, the isolator withstood both cycles without any problems, failures or load reductions. The increase in load due to the action of the pins started after the 300 mm displacement of the first cycle. The data were within allowable limits.

5.5.3 Limit Life Test

The aim of this test phase was to evaluate the isolator's residual capacity to accommodate load cycles beyond design specifications. It was conducted using the same parameters as in § 5.5.1. The test was interrupted after 9 cycles, corresponding to the 26th cycle from the start of the test, due to the fact that maximum load had almost gone down to 50% of that recorded between the 11th and 15th cycles of the Behaviour Test.

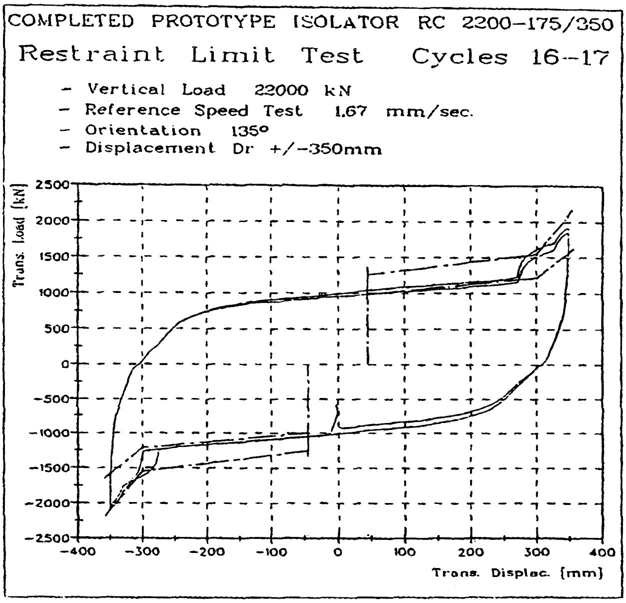

Figure 2. Restraint Limit Test

6 Installation

Given the very compact shape of the isolators (see Figure 1), their installation was easily achieved in a very short time. Figure 3 depicts a view of the isolators on the pier caps before deck installation, while Figure 4 shows the platform after the work has been finished.

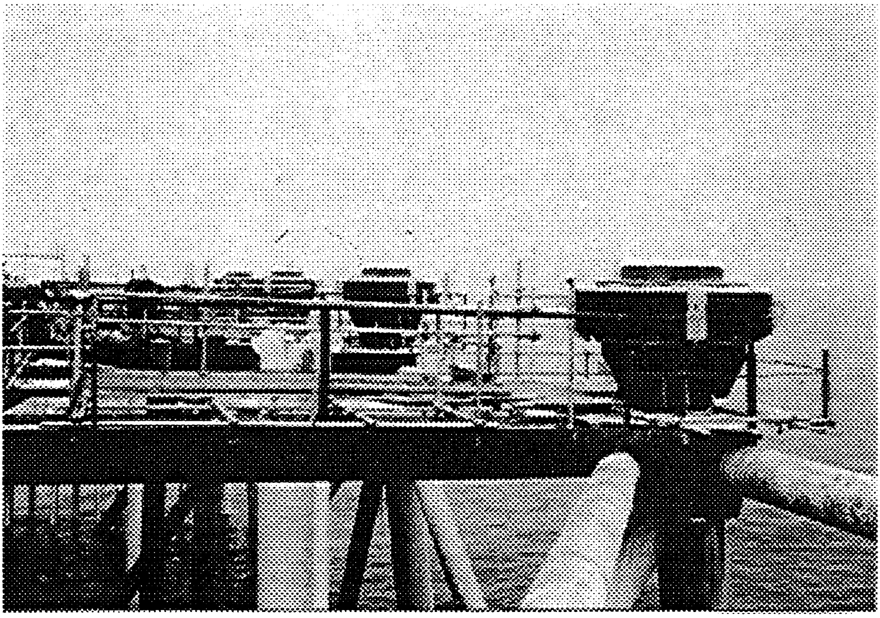

Figure 3. Isolators as installed on the pier caps

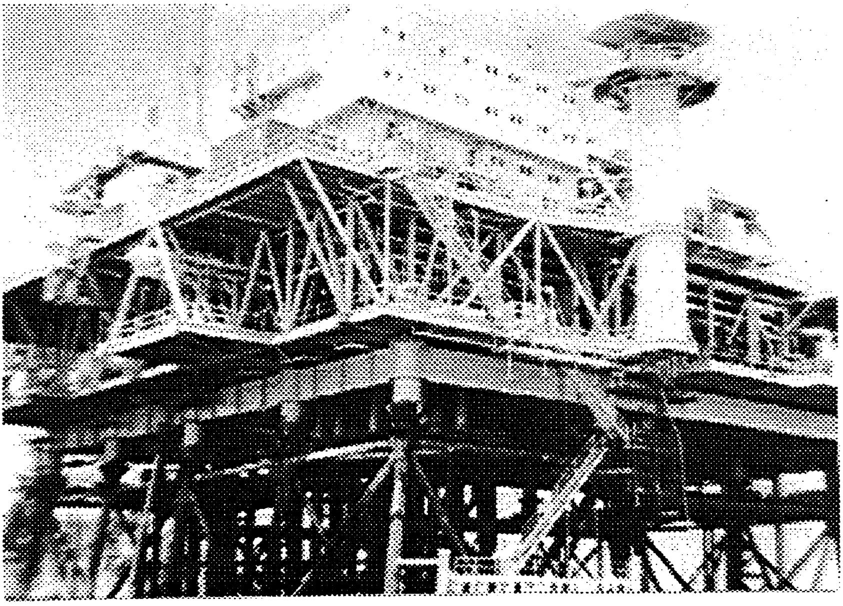

Figure 4. South View of Refurbished Chirag 1 Platform

7. Conclusions

The Chirag 1 Platform has been operational since August 1997. The works were completed ahead schedule. FIP contributed to such work progress by delivering the devices in less than five months from the date they were ordered. The positive experience derived from this first pioneering effort with this type of application leads to the following conclusions:

- The installation of a seismic isolation system in an offshore platform is relatively easy; at least, as it is so with bridges.
- Beyond the obvious case of newly constructed platforms, installation is feasible even in cases of retrofit where deck removal is not necessary so long as appropriate measures are taken.
- Seismic Isolation, is undoubtedly a cost effective alternative to traditional pile strengthening and offers additional non-structural advantages (*i.e.*: personnel safety, reduction of environmental hazards, etc.).

As it regards newly conceived oil platforms, where seismic loads can be considered *a priori*, and where efficient dimensioning of critical structural elements can avoid important structural damage, the isolators nonetheless permit a reduction of accelerations and relative inertial forces on the deck and the equipment installed in it, and thus permit a restoration of maximum operational conditions even after a major seismic attack.

Acknowledgement

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