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Research paper

Influence of weak layers on seismic stability of submarine slopes

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ABSTRACT

Instability of submarine slopes and the risk posed by submarine slides are a concern in offshore activities related to energy, communications, food production and tourism. In particular, much of the offshore infrastructure needed for the extraction and transportation of hydrocarbons in deep waters are located on the continental slope, with significant exposure to the risk posed by a submarine landslide. Recent studies of the triggering mechanisms of a submarine landslide show that the combination of a predisposition factor like a weak layer within the soil profile, together with a "short duration trigger" such as an earthquake, is one of the most likely scenarios for slide initiation. In this paper, the influence of a weak layer on the stability of a submarine slope before, during and after a strong earthquake event is examined. The slope under study is located in the southern part of the Gulf of Mexico, on the continental slope in a water depth of 500 m.

The slope stability assessments in the study include static slope stability using the limit equilibrium method and the finite element method, pseudo-static analyses using the limit equilibrium method, as well as 1-D and 2-D non-linear dynamic analyses using the finite element method. The earthquake-induced shear strains within the soil deposit are a key parameter in the slope stability assessment. Therefore, the dynamic analyses focused on estimating the maximum and permanent shear strains within the soil profile.

Given the complexity of the problem, the decrease of the soil strength during and after the earthquake loading was estimated through a decoupled approach based on the calculated shear strains and results of advanced laboratory tests.

The results of the study show quantitatively the important role of a weak layer in the initiation of a submarine landslide under a strong earthquake.

1. Introduction

The oil and gas industry is the main provider of energy all over the world despite the increasing interest in developing other energy sources. Offshore structures and subsea installations are necessary for the development of oil and gas fields and extraction of hydrocarbons from reservoirs found at deep-water offshore sites. Some of these installations need to be placed in areas where there is evidence of slide activity.

It is particularly important to assess the stability of submarine slopes in seismically active areas during the process of site selection for seabed installations. Earthquake loading is an effective trigger for initiation of submarine slides because of two processes. First, during the earthquake there is an increase of the driving stresses on a potential failure surface due to the inertial forces. Second, the cyclic earthquake-induced stresses and strains may increase the pore pressures and reduce the soil shear strength below the values required for the equilibrium of the slope. In the presence of weak or anomalous layers, the latter mechanism may manifest itself as delayed, creep-type failure sometime after the earthquake.

The aim of this paper is to quantify the influence of weak layers on the stability of submarine slopes in all the stages of a seismic event. This was done by studying the same slope for two conditions; with and without a 1 m thick weak clay layer specified at 25 m depth. For the purposes of this study, a weak layer is defined as a soil layer with lower strength and stiffness relative to the neighbouring layers. This is the same definition as Locat et al.

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(2013), who defined weak layers from a geotechnical perspective. The key dynamic geotechnical properties of the weak layer, i.e. the undrained shear strength and shear stiffness, were set to 50% of the values of the neighbouring layers.

To quantify the influence of a weak layer on the seismic stability of a submarine slope, the following analyses were done (the software used for doing the analyses is shown in parenthesis):

- Before the Earthquake: Static slope analyses were done using the Limit Equilibrium Method (SLOPE/W) and the Finite Element Method (PLAXIS 2D) to estimate the factor of safety of the slope before the seismic event.
- During the Earthquake: Pseudo-static stability analyses (SLOPE/W) were done to estimate the yield acceleration coefficient K_y that would lead to a safety factor of one. Non-linear 1-D (AMPLE) and 2-D (PLAXIS 2D) dynamic response analyses were also done. The purpose of the dynamic analyses was to identify the clay layers experiencing large earthquake-induced shear strains. These were later used together with advanced laboratory test data to estimate the degradation of the soil shear strength. It should be noted that the degradation of soil shear strength is mainly due to generation of excess pore pressures during cyclic loading. However, prediction of these excess pore pressures is very difficult and work done mainly by Andersen et al. (2012) showed that induced shear strain is a good indicator for assessing the shear strength degradation. Nevertheless, the shear strength degradation during cyclic loading was estimated based on a suggested approach that makes use of the so called Failure Interaction Diagrams (FID's). The suggested FID approach to estimate the cyclic shear strength $\tau_{cy,f}$ was proposed given that the estimated induced shear strains in the soil layers didn't pass the shear stress peak of Site 1 zone clays, which is a precondition to applying Andersen's procedure.
- After the Earthquake: Static slope analyses were done using the Limit Equilibrium Method (SLOPE/W) to obtain the post-earthquake static factor of safety considering the decrease of shear strength based on four main factors: soil structure disturbance, excess pore pressure generation, strain softening and undrained creep. The estimation of the strength reduction was carried out based on available laboratory test data.

The Site 1 region in the southern part of the Gulf of Mexico was used as a case study to demonstrate the analyses described above. The National Oil Company of Mexico (PEMEX) is planning to develop a natural gas reservoir in this region. The gas reservoir is located on the continental slope, about 55 km from land, in a water depth of about 1200 m (Fig. 1). In 2008, Fugro GeoServices Inc. performed the geophysical survey and Fugro Chance de Mexico, S.A. de C.V. carried out the geotechnical field investigation of the area (Fugro Chance de México, 2009a, 2009b; Fugro GeoConsulting, 2009). The area is seismically active (Figs. 2 and 3) and the site is influenced by the subduction zone in the Pacific Ocean, active volcanoes nearby and the transform zone in the Caribbean Sea. There is concern that, once the field is developed, an earthquake-triggered submarine landslide could impact the seabed installations and disrupt the natural gas production. It is therefore important to assess the stability of the relevant submarine slopes before, during and after the (design) earthquake by means of numerical simulations.

2. Weak layers

Weak soil layers are a likely precondition involved in submarine landslides (L'Heureux et al., 2012; Norwegian Geotechnical Institute, 1997). The presence of weak layers is one of the reasons suggested for the initiation of the Storegga slide (Bryn et al., 2005a, 2005b; Solheim et al., 2005) where slide-prone soil layers have been identified in contouritic clay deposits (contourites). These contourites were formed during interglacial periods where ice-related sedimentation was at its minimum. As the glaciers returned to the margins, the contourites were rapidly buried under glacial marine deposits forming a softer layer beneath the strong, overconsolidated glacial deposits. The loss of shear strength in these weak layers during an earthquake might have initiated the Storegga slide. Similar to the Storegga slide, the actual sliding mechanism in the Grand Banks slide is quite complex (Mosher and Piper, 2007), and leads to the belief that the seismic response of the weak layers was one of the key factors in the initiation of the Grand Banks slide (Locat and Lee, 2009).

The need to investigate the role of weak layers, in triggering submarine slides, was one of the main conclusions of the workshop "Scientific Ocean Drilling Behind the Assessment of Geo-hazards from Submarine Slides" held in Barcelona in 2006 (Camerlenghi et al., 2007; Urgeles et al., 2007).

In this study, the shear strength and stiffness of the weak layer were set 50% lower than for the bordering layers, based on previous studies that suggest that a contrast in strength and stiffness between weak layers and neighbouring layers of about 50% is not uncommon (L'Heureux et al., 2012; Picarelli et al., 2012; Steiner et al., 2012). The contrast in strength and stiffness between neighbouring layers is often due to sediments having been deposited in a different geological setting.

3. Site characterization for the case study

The Site 1 area extends over the edge of the continental shelf and upper continental slope in the margin of the southern portion of the Gulf of Mexico. Tectonically, the continental margins surrounding the Gulf of Mexico are passive and are characterized by features commonly associated with passive margins, such as a relatively wide continental shelf and a gentle slope extending into deeper water. Sedimentation is controlled by the presence of rivers and streams that provide clastic sediments from the Mexican interior to coastal areas, and carbonate platform sedimentation related to the tropical climate. The dominant geological processes acting on the region include stratified marine sediment deposition, periodic rupture (faulting) of the slope, movement and deposition processes, non-tectonic faulting and normal oceanographic processes, such as waves and currents. In locations such as the area of the Site 1 polygon, the continental shelf is comparatively narrower, and this factor may facilitate the transport of inner shelf sediments to the continental slope. Secondary regional geological processes may include occasional episodes of volcanism and earthquakes (Fugro GeoConsulting, 2009).

In the Site 1 project, 9 potentially unstable slopes, ranging from 0.1 to 9.2°, were identified during the high-resolution shallow, 200 m below seafloor, geophysical survey carried out by Fugro GeoServices Inc. (Fugro Chance de México, 2009a; Fugro GeoConsulting, 2009). The proposed slope geometry for this analysis is equivalent to the submarine slope with the largest slope angle found in the geophysical exploration. The suggested slope model is a composite slope made of two slopes: in the upper part, a 10° slope angle with a 600 m length in the horizontal direction; then in the lower part a 5° slope angle with a 400 m length in the horizontal direction (Fig. 6).

3.1. Soil geotechnical properties

In situ and laboratory tests were carried out by Fugro (Fugro Chance de México, 2009a, 2009b) to obtain the geotechnical