Applied Ocean Research 78 (2018) 167–179

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

# Probability analysis of submarine landslides based on the Response Surface Method: A case study from the South China Sea

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ARTICLE INFO

*Keywords:*
Reliability analysis
Submarine landslide
First Order Second Moment method
Response Surface Method
Gaussian Process Regression
South China Sea

ABSTRACT

As deep-sea engineering develops, it becomes essential to analyze the stability of submarine slopes when considering the stability of submarine foundations or evaluating the safety of offshore structures. However, the traditional method for analyzing slope stability does not give adequate consideration to the uncertainty of soil properties, and so the reliability method has been proposed and used to settle the variation of soil parameters. Regarding the northern slope of the South China Sea, the present paper summarizes its geomorphic features, seismic characteristics, and the soil strength at certain boreholes. A typical slope section is chosen with which to conduct probability analysis using the polynomial-based Response Surface Method (RSM) and the Advanced First Order Second Moment method(AFOSM). A novel form of the RSM based on Gaussian Process Regression (GPR) is also proposed and applied in this case to approximate the limit state function, and its efficiency is confirmed. The simulation results of Latin-hypercube analysis are set as the benchmark for the other methods. The influences of slope gradient and seismic action on the stability of submarine slopes are also investigated.

## 1. Introduction

The exploration for and exploitation of ocean oil and gas resources have developed from shallow waters to deep waters and even to ultra-deep waters. With the ongoing development and utilization of marine resources, engineering facilities are being constructed more often in deep waters [1], making marine geological hazards such as submarine landslides unavoidable problems for geotechnical engineers [2]. Evaluating the stability of submarine slopes is an important part of studying submarine geo-hazards. When a submarine landslide occurs, the released energy propagates upward, generating waves and even tsunamis that can damage offshore structures [3]. Meanwhile, the slip mass develops gradually into a debris flow on the seabed and appears “hydroplaning” in the front [4,5]. Such high-speed flow can have an enormous impact on platform foundations [6,7].

As shown in Fig. 1, the main triggers of submarine landslides are (i) earthquakes and faulting, (ii) gas and gas-hydrate disassociation, and (iii) rapid sedimentation [8]. Among 534 submarine landslides, more than 40% (225 in total) were caused by earthquakes, making earthquakes the most common trigger [9].

Most submarine landslides occur on outer continental shelves and upper continental slopes. In recent decades, there have been comprehensive studies of (i) the southeast slope of the United States [10], (ii) the outer shelf of Norway [11,12], (iii) the Mediterranean Sea [13–15], (iv) the Gulf of Mexico [16], (v) the continental slope of West Africa [17], (vi) Japan’s southwest coast [18], and (vii) the northern slope of the South China Sea [19]. The regional distribution of the main areas for submarine landslides is shown in Fig. 2.

Denlinger and Iverson used the limit-equilibrium method to evaluate the stability factor and liquefaction potential of submarine slopes by assuming homogeneous infinite slopes with steady seepage, showing that such slopes undergo Coulomb failure before liquefaction [20]. Gatmiri developed a simplified finite-element method for studying wave-induced pore pressures and effective stresses in saturated submarine sediments with the consideration of vertical nonlinear distribution of the pore pressures and effective stress [21]. Li et al. revealed the triggering mechanism of submarine landslides caused by gas-hydrate disassociation and proposed a quantitative analytical model of submarine slope stability that considered natural gas-hydrate decomposition [22]. Nian et al. showed how to obtain the safety factor of a submarine slope under extreme wave load and established an equilibrium equation between external work and interior energy dissipation based on the upper-bound theorem of limit analysis [23]. Dey et al. used the large-deformation finite-element technique to simulate a submarine slope with a weak clay layer by considering the undrained shear strength and strain-softening model of marine clay [24].

However, conventional deterministic analytical methods do not account for the variability of the physical and mechanical parameters of

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https://doi.org/10.1016/j.apor.2018.06.018
Received 14 January 2018; Received in revised form 8 June 2018; Accepted 25 June 2018

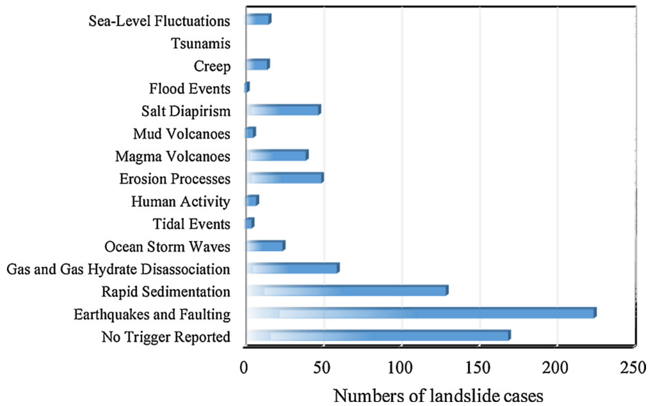


**Fig. 1.** Numbers of landslides according to trigger.

marine sediments. Therefore, it is unreasonable to use the deterministic safety factor $Fs$ to evaluate the possibility of slope instability; even if $Fs > 1$, we cannot be completely certain that the slope will not fail. Ochoa et al. pointed out that assessing the risk of a submarine landslide clearly involves much uncertainty [25]. Therefore, a reasonable approach is to use reliability analysis and probability theory while quantifying the uncertainty involved [26–30].

## 2. Analytical methods for slope reliability

When analyzing the reliability of a slope, the performance function is usually expressed as

$$Z = g(X) = g(X_1, X_2, \ldots, X_n) = Fs - 1 \tag{1}$$

where $X_1, X_2, \ldots, X_n$ are random variables and $Fs$ is the safety factor. The reliability index can be expressed as

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{2}$$

where$\mu_Z$ and $\sigma_Z$ are the mean and standard deviation, respectively, of the performance function $Z$. We assume that $Z$ has a normal distribution and that the probability of slope failure is

$$p_f = P(Z < 0) = \Phi(-\beta) \tag{3}$$

If $Z$ involves many random variables, it can be difficult to determine its distribution. In such cases, it is easier to determine the statistics of the random variables, such as their mean and variance. In engineering, it is practical to use these statistics and the probability distribution of the variables to perform reliability analysis [31].

### 2.1. First Order Second Moment method

The First Order Second Moment (FOSM) method is commonly used for reliability analysis. Fundamental, this involves expanding the performance function as a Taylor series about a certain point and retaining only the first-order term [32]; the reliability index is obtained from the mean and standard deviation of the random variables [33]. The versions used most commonly are the mean First Order Second Moment (MFOSM) method and the advanced First Order Second Moment (AFOSM) method.

The MFOSM method involves expanding the performance function as a Taylor series about the mean value. However, the mean-value point is not necessarily on the limit-state (LS) surface, which may lead to large errors. In contrast, in the AFOSM method, the expansion point is on the failure surface and the distribution of the random variables is taken into consideration, making the AFOSM method a considerable improvement over the MFOSM method.

Take $x^* = (x_1^*, x_2^*, \ldots, x_n^*)^T$ as a point on the limit state surface $Z = g(\mathbf{X}) = 0$, i.e., $g(x^*) = 0$. Expand Eq. (1) as a Taylor series about $\boldsymbol{x}^*$ and retain only the first-order term to obtain

$$Z = g(x^*) + \sum_{i=1}^{n} (\frac{\partial g}{\partial X_i})_{x^*}(X_i - x^*) \tag{4}$$

Substitute the mean and standard deviation of $Z$ into Eq. (2) to obtain

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{g(x^*) + \sum_{i=1}^{n} (\frac{\partial g}{\partial X_i})_{x^*}(\mu_{X_i} - x_i^*)}{\sqrt{\sum_{i=1}^{n} [(\frac{\partial g}{\partial X_i})_{x^*}]^2 \sigma_{Xi}^2}} \tag{5}$$

where $\mu_{Xi}$ and $\sigma_{Xi}$ are the mean and standard deviation, respectively, of random variable $X_i$. Define the sensitivity coefficient of the variables as

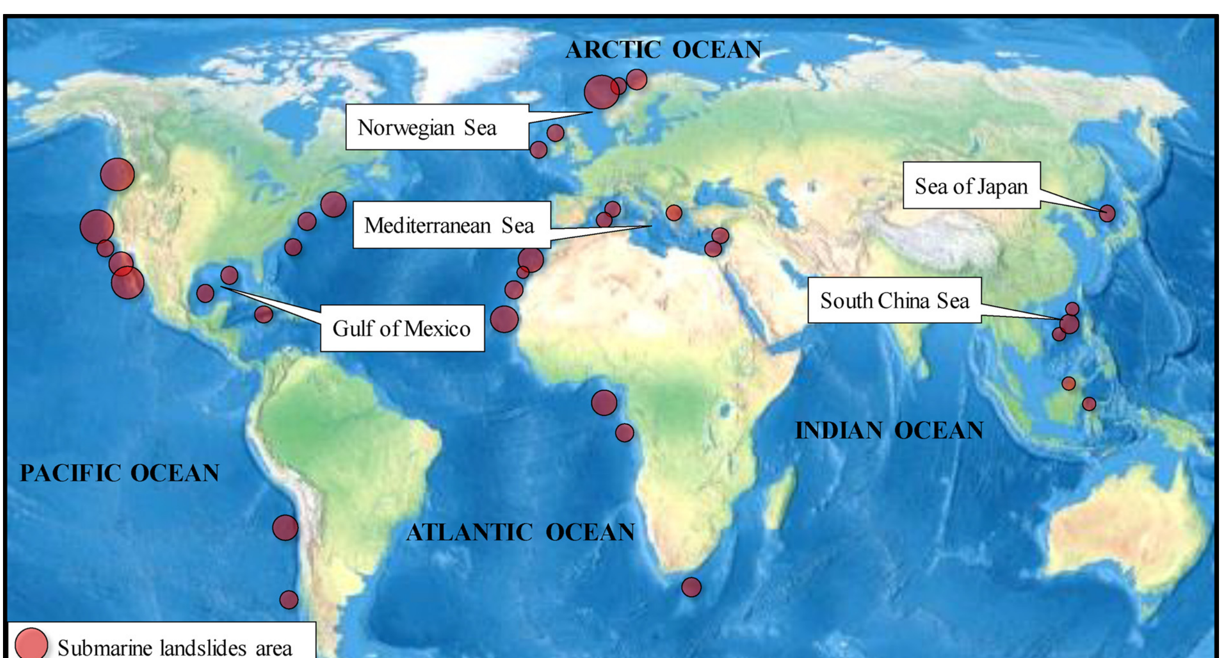


**Fig. 2.** Regional distribution of main areas for submarine landslides.