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Seismic risk assessment of Corinth Canal Greece

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Abstract
Corinth canal is one of the most important navigation projects made in Greece and plays a significant role in marine transportation connecting the Ionian sea to the West through the Corinth Gulf and Saronikos Gulf to the Aegian sea to the East. It has a total length of 6.3km and due to its steep slopes possesses serious slope instability problems. This work deals with the effect that local seismicity has upon Corinth Canal by assessing the corresponding site specific seismic risk. Special parameters such as the expected peak ground acceleration and the Arias intensity which are close related with local slope instabilities have been determined. All well known near by seismic faults have been taken into consideration and the most dangerous seismic sources which can cause serious damage to the canal have been defined.

Keywords: Seismic risk, Arias intensity, Corinth Canal, Greece

1 Introduction

Corinth Canal is 6.3 km long and geographically is located in the eastern border of the Corinth Gulf in the center of a neotectonic depression. It is a narrow piece of land that connects Peloponnesus with the mainland of Greece and the Gulf of Corinth with the Saronic Gulf, Figure 1.

Corinth canal is one of the most important projects that were made in Greece in the 19^{th} century for navigation, railroad and highway connection. The cutting of the canal begun in 1882 and it was completed in 1893. Slopes in the canal exhibit inclination 75^o and maximum height ~ 79m above the sea level. The water depth is ~8m and the width of the canal is ~24.5m on the sea surface and ~21m on the sea bottom.

Since the opening of the canal in 1893 several problems due to local slope instabilities have been reported, Figure 2. Most of them occur in the Peloponnesus side. During the 2^{nd} half of the 20^{th} century 16 local slope instabilities have been occurred in this area.

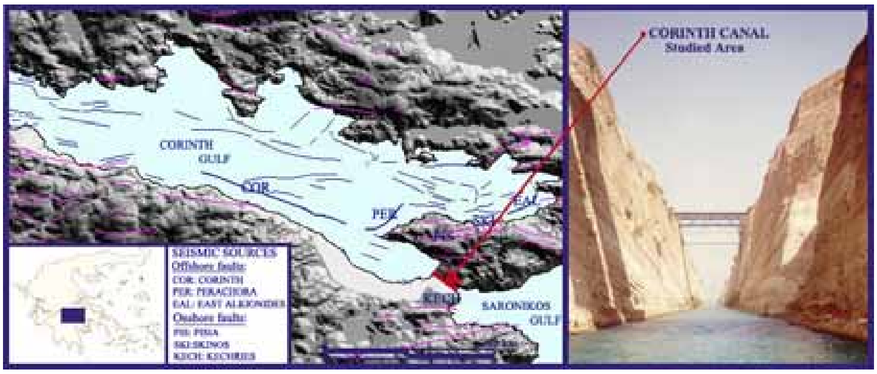

Figure 1: Active faults in the nearby region of Corinth Canal. A view of the NW border of the canal is also depicted.

The cause of this problem is complicated. It can be assigned to several reasons due to the tectonic and geotechnical complexity of the Neogene formations in the canal and due to the lack of protecting walls for over 4 Km along the canal (wave erosion in the base of the slopes), (Andrikopoulou et al [1], HCMR [5]).

High seismicity in the nearby area of the Corinth Canal can be another reason that can cause slope instabilities especially at the sites of the slopes that are characterized with low safety factor. Several studies in the canal have pointed out that wedge type instabilities are likely to occur during periods of increased seismicity. Especially when fault planes can be combined with extensional or stress relief fissures, (e.g. Andrikopoulou et al [1]).

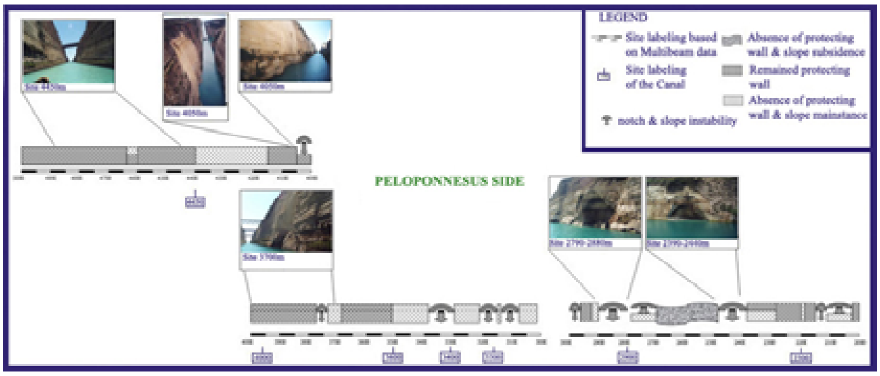

Figure 2: Characteristic subsidence along Corinth Canal, by HCMR [5].

Earthquake activity is one of the principal reasons which create the conditions needed that will finally lead in local slope instability phenomenon, either by crack growth or by the formation of new ruptures. Considering this problem we conducted a seismic hazard investigation in the eastern Corinth Gulf. All known active faults were outlined in the source model and hazard maps were assessed with respect to peak ground acceleration and Arias intensity. The main goal of this study was to define the most dangerous seismic source and the areas inside the canal that will be probably affected.

2 Seismic hazard assessment

2.1 Source Model

Tectonic activity that takes place in this area has been clearly expressed by the historical and recent seismicity, Figure 3. Large earthquakes have occurred in the area of the Gulf of Corinth, with high intensity distribution. Some indicative examples from the previous century were the 1928 (Ms = 6.3 R), 1953 (Ms = 5.8 R) and the 1981 Alkionides earthquakes (Ms = 6.7 & 6.4R). Their catastrophic distribution affected seriously the narrow area of the Corinth Canal.

Gulf of Corinth has been described as a complex asymmetric half-graben whose geometry varies significantly along its length. Extension is accommodated by a series of major active faults It has maximum water depth 900 m and contains Quaternary sediments over 1Km thick. Further more Stefatos et al [11] presented a detailed map of the gulf containing 66 normal offshore faults most of them parallel along its axis. These faults are recognized in two basic categories as major and as minor faults. Major faults downthrown Plio-Quaternary sediments, define the actual margin of the gulf and they are usually associated with high fault scarps. These faults along the northern margins dip to the south while the faults on the southern margin dip to the north.

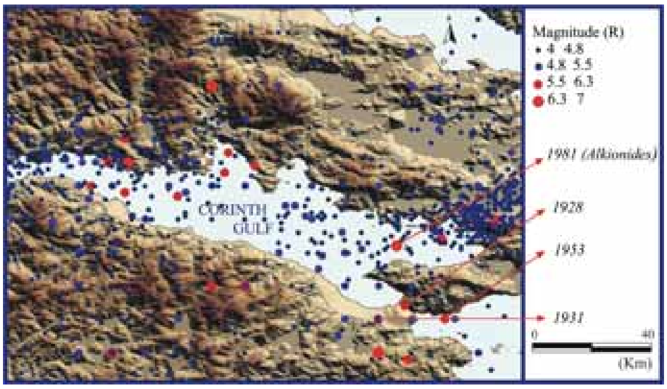

Figure 3: Seismicity map of the Gulf of Corinth, during 1900-2004. Some representative strong earthquake epicenters in the close area of the Corinth Canal have been indicated with arrows.

One of the most important tasks for assessing a seismic hazard investigation for Corinth Canal was the identification of all possible earthquake sources (active faults) which have significant potential for future earthquakes. A GIS platform (ArcView3.2) was created containing all the relevant information for the studied area (geological, topographic, seismicity, neotectonic).

Linear seismic sources (active faults) that were chosen as an input in our model are presented in Figure 1. This proposed source model is consisted with the well known submarine faults Corinth, Perachora and East Alkionides and the onshore faults Pisia, Skinos and Kechries.

To select these seismic sources we were based on previous studies that were concentrated on high resolution seismic reflection surveys over the Gulf of Corinth, (Stefatos et al [11]), on macroseismic observations of the 1981 Alkionides earthquakes, (Jackson et al [7]), and geomorphological investigations, (Noller et al [8]).

Based on macroseismic information Pisia and Skinos faults were also selected as possible significant seismic sources. These faults is evident that had been reactivated during the Alkionides earthquakes main aftershock on 25-2-1981 with magnitude 6.4 R,. Pissia and Skinos faults exhibits an E-W direction and their total length ranges to 15km and 9km, respectably, (Jackson et al [7]).

Considering the offshore faults Corinth, Perachora and East Alkionides, it has been reported that they remained active during Holocene, (e.g. Stefatos et al [11]). In addition, these faults provide direct evidence of a coseismic activity based on observed elevated fossil shorelines and marine terraces in various places along the southern coasts of the Gulf of Corinth. Among them, Corinth submarine fault is the longest fault on the southern margin of the Corinth Gulf and exhibits the characteristics of a continuously active fault. It trends WNW-ESE almost parallel to the coastline for a length of about 26km and dips at approximately 35-46^{o} to the north, producing a scarp of a height of 650m height.

Furthermore Perachora offshore fault has a length of about 11.2km and dips also to the north at an angle of 32-48^{o}degrees. Finally the East Alkionides fault is about 7.8km long dips approximately to NW and indicates a constant activity over the last 127.000 years. The characteristics of the selected for the present seismic hazard analysis faults that can affect Corinth canal are depicted in Table.1

Table 1: Seismogenic faults that can influence Corinth Canal.

ID	Fault	Length (Km)	Max Expected Magnitude	Annual Earthquake Rate
1	KECHRIES	7.8	5.4	0.44
2	ALKIONIDES	8.5	5.4	0.44
3	PERACHORA	11.2	5.7	0.23
4	PISIA	15	5.9	0.14
5	SKINOS	9	5.5	0.34
6	CORINTH	26	6.4	0.05

2.2 Attenuation Laws

Several attenuation laws have been proposed for Greece in the last 20 years, (e.g. Tselentis [14], Theodulidis & Papazachos [12], Scarlatoudis et al [10] and many others), derived by either a Greek strong-motion database or from a wider region strong-motion database. These empirical laws usually describe a ground motion parameter such us acceleration, velocity and displacement in relation with distance and earthquake magnitude. Some representative attenuation laws for Greece of a 6Ms earthquake magnitude, are presented in Figure 4.

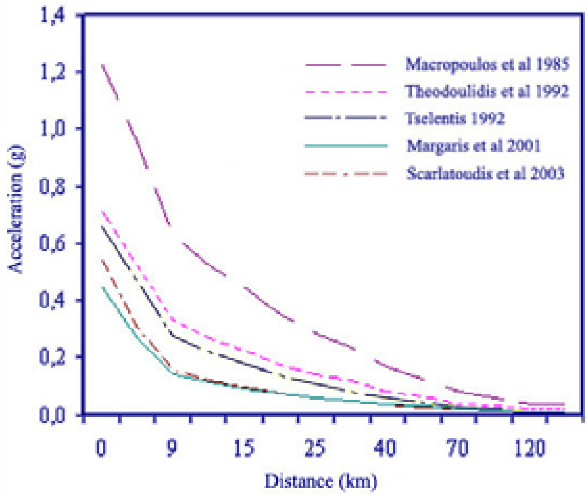

Figure 4: Peak ground acceleration attenuation laws for Greece of a 6Ms earthquake magnitude.

Theodulidis & Papazachos [12] proposed an attenuation relationship that has been widely used in seismic hazard computations and its efficiency has been proved (eqn. 1). The authors used a strong motion database consisted of 105 horizontal components from shallow earthquakes in Greece of magnitude 4.5 to 7 and 16 horizontal components from four shallow subduction earthquakes in Japan and Alaska of magnitudes 7.2 to 7.5. The data covered a wide range of epicentral distances $9km \leq R \leq 128km$.

$$Lna = 3.88+1.12Ms-1.65\ln(R+15) + 0.41S+0.71P \quad (1)$$

where a is the acceleration in %g, Ms the surface wave magnitude, R the epicentral distance in km, S is equal to 0 at alluvium sites and 1 at rock sites and P is equal to 0 for 50 percentile values and equal to 1 for 84 percentile values.
It is important to mention, as the length and quality of the Greek seismic catalogs increases attenuation laws become more efficient.

Arias intensity is another ground motion parameter which is strongly related with the amplitude, the frequency content and the duration of the earthquake ground motion. It is defined as (Arias [2]):

$$I_a = \frac{\pi}{2g} \int_0^{\infty} \left[a(t) \right]^2 dt \qquad (2)$$

Where *Ia* is the Arias Intensity in units of velocity and *a(t)* the acceleration time history in units of g.

Arias Intensity is an objective measure of the degree of shaking between different earthquakes and correlates well with distributions of earthquake induced landslides and soil liquefaction. Recently Arias Intensity started to be used in seismic hazard landslide mapping.

Keefer & Wilson [6] were the first who introduced an Arias Intensity attenuation law and they tried to correlate this ground motion parameter with earthquake induced landslides. The authors, defined thresholds of Arias Intensity beyond which occurrence of certain type of seismic triggered slope instability becomes possible: Type I: falls, disrupted slides - Ia threshold of 0.11m/sec; Type II: slumps, block slides and earth flows - Ia threshold of 0.32m/sec; Type III: lateral spreads and flows - Ia threshold of 0.54m/sec.

Faccioli [4] introduced an empirical attenuation law for the Mediterranean region which takes into account source rupture directivity. Although this relationship can be applied in several tectonics regions it can not be easily used in an automatic probabilistic hazard computation. Focusing, in the area of Greece and Italy, Piacello et al [9], presented attenuation laws for Arias Intensity and other ground motion parameters. The authors used 230 horizontal components referred to 18 different earthquakes. Travasarou et al [13], proposed another empirical relationship (eqn. 3) to estimate Aria Intensity as a function of magnitude (M), distance (R), fault mechanism (F_N, F_R) and site category (S_C, S_D):

$$\begin{aligned} \ln I_a &= 2.8 - 1.981 * (M - 6) + 20.72 * \ln(M / 6) - 1.703 * \ln(\sqrt{R^2 + 8.78^2}) \\ &+ (0.454 + 0.101 * (M - 6)) S_C + (0.479 + 0.334 * (M - 6)) S_D \\ &- 0.166 * F_N + 0.512 * F_R \end{aligned} \qquad (3)$$

Equation 3 is based on 1208 recorded strong ground motion data from 75 earthquakes in active plate margins and is applicable for earthquakes with $4.7 \le Ms \le 7.6$ and $0.1 \le R \le 250$Km. In comparison with previous relationships Travasarou et al [13], found out that for large magnitude earthquakes (Ms>7) Arias Intensity was significantly overestimated whilst for smaller magnitude events ($Ms \le 6$) it was underestimated.

2.3 Probabilistic PGA and Arias Intensity maps

The model for the occurrence of ground motions at a specific site in excess of a specified level is assumed to be that of a Poisson process. This follows if the occurrence of earthquakes is a Poisson process, and if the probability that any one event will produce site ground motions in excess of a specified level is independent of the occurrence of other events. The probability that a ground motion level *z* is exceeded at a site in unit time is thus expressed as:

$$P(Z > z) = 1 - e^{-\nu(z)} \quad (4)$$

Where $\nu(z)$ is the mean number of events per unit time in which Z exceeds z. With N seismic sources, and seismicity model parameters S_n for each source n, the mean number of events pr. unit time in which ground motion level z is exceeded can be written as:

$$\nu(z) = \sum_{n=1}^{N} \nu_n(z|S_n) \quad (5)$$

where

$$\nu_n(z|S_n) = \sum_{i,j} \lambda_n(M_i|S_n) P_n(r_j|M_i S_n) G_n(z|r_j M_i S_n) \quad (6)$$

$\lambda_n(M_i | S_n)$ is the mean number of events per unit time of magnitude M_i ($M_i \in [M_{min}, M_{max}]$) in the source n with seismicity parameters S_n. $P_n(r_j | M_i S_n)$ is the probability that a significant site -source distance is r_j, ($r_j \in [r_{min}, r_{max}]$) given an event of magnitude M_i in source n with seismicity parameters S_n. $G_n(z | r_j M_i S_n)$ is the probability that the ground motion level z will be exceeded, given an event of magnitude M_i at distance r in source n with seismicity parameters S_n. The three functions $\lambda_n(M_i | S_n)$, $P_n(r_j|M_i S_n)$ and $G_n(z|r_j M_i S_n)$ model the inherent stochastic uncertainty in the frequency of occurrence and location of earthquakes, and in the attenuation of seismic waves.

Given that the mean number of events per unit time for which Z exceeds z is expressed for example as $1/T_R$, where T_R is the return period (inverse of annual exceedance probability), then the number of events in a time period T (e.g. the life time of a certain construction) for which Z exceeds z is given by T/T_R and the probability for Z exceeding z during that life time T is given by:

$$P(Z>z) = 1 - e^{-T/TR} \quad (7)$$

For a lifetime T of 50 years and a return period TR of 475 years (annual probability of exceedance 0.211 x 10-2) the probability for Z exceeding z becomes 0.1, corresponding to 90% probability that this size ground motion is not exceeded in 50 years. With several seismic sources, described through particular model parameters, the mean number of events per unit time in which the ground motion level is exceeded can be expressed specifically, involving functions that model the inherent stochastic uncertainty in the frequency and location of earthquakes, and in the attenuation of the seismic waves.

Besides this natural uncertainty, there is also an element of uncertainty associated with the variability of model parameters. This source of uncertainty is accounted for by regarding these parameters as random variables, whose discrete values are assigned weights reflecting their likelihood.

The algorithm outputs directly the Probabilistic Seismic Hazard Analysis (PSHA) in contour maps of acceleration (in g) that has a 90% probability of not being exceeded in various returning periods for the seismic basement of the region of Patras. The hazard calculations are been performed using the SEISRISKIII algorithm by Bender & Perkins [3].

The above mentioned seismic source model which is proposed for the Corinth Canal area and the attenuation model of horizontal peak ground acceleration (PGA) described by Theodulidis & Papazachos [12] using rock site conditions were used to create seismic hazard maps of PGA, for a period of 50 years with 90% probability of non-exceedance. Figure 5 depicts the obtained results.

To describe a seismogenic landslide hazard map in the wider area of Corinth Canal, this seismic hazard computational procedure was repeated for Arias Intensity. For this purpose we simply used the attenuation law for Arias Intensity described by eqn. (3). This attenuation relationship was applied describing rock site conditions and normal fault mechanism which characterizes the geological and neotectonic setting in the wider area of Eastern Corinth Gulf.

Figure 6 shows the results of the regions seismic hazard corresponding to Arias Intensity, a parameter close related to slope instabilities.

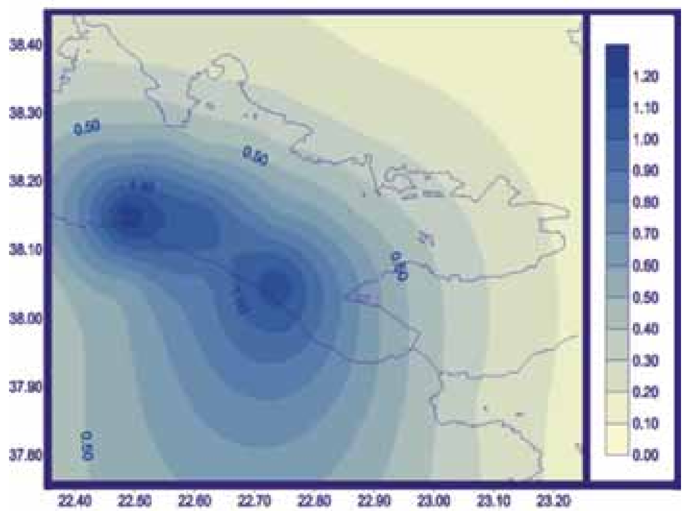

Figure 5: PGA hazard map in units of g (%g) for the region of interest.

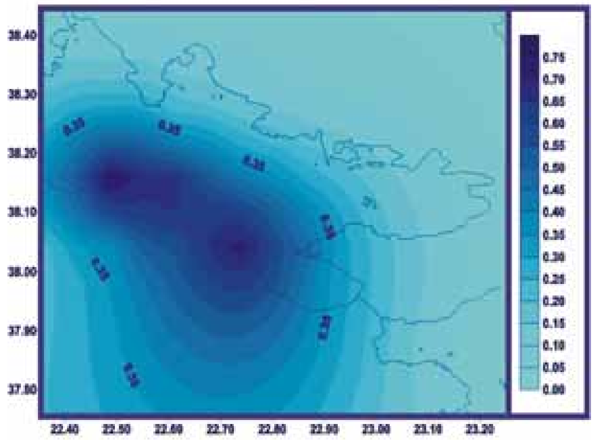

Figure 6: Ia hazard map in units of m/sec (%m/sec) for the region of interest.

3 Conclusions

The results of the seismic hazard analysis show the significant contribution of the nearby to the canal faults such as the Corinth offshore fault which has the seismic potential of 6.4R. The maximum expected acceleration in the site of the canal is high in the order of 0.45g. The corresponding Arias intensities are of the order of 0.30 m/sec. Both parameters according to the literature (e.g. Keefer & Wilson [6]) can seriously affect the steep canal slopes and mainly cause falls and disrupted slides. Additionally into a lesser extent a series of slumps, block slides and earth flows is possible to occur. Concentration of these earthquake induced instabilities phenomenon are mainly expected to appear towards the NW side of the canal.

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