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LIQUEFACTION RISK ASSESSMENT BY THE USE OF GEOPHYSICAL TECHNIQUES: THE TEST AREA OF NAFPLION CITY, GREECE

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Abstract

An efficient and cost effective site characterization, with regard to the seismic hazard and liquefaction risk assessment, was accomplished with the aid of geophysics in the area, where the Nafplion city of Greece is expanding. The methodology adopted includes the recognition of the possible earthquake sources of the wider region, their modelling, in order to stochastically simulate the strong ground motion at the investigation area, and finally the calculation of the liquefaction risk. The investigation area was suspected of high liquefaction potential since the foundation ground consists of loose sandy silt with very shallow aquifer. The geophysical techniques considerably contributed to the detection and characterization of possible local seismic faults with the implementation of gravity and seismic methods. Special emphasis was given to the seismic depth migration and particularly to the construction of valid velocity models, in order to precisely calculate the dips of the possible faults. Additionally the geophysical techniques provided the near surface velocity structure for the calculation of the amplification of the seismic motion up to the surface, also required for the final estimation of the liquefaction risk. The seismic methods (seismic reflection, seismic refraction, seismic modelling, MASW, multichannel analysis of microtremors and crosshole investigations), if combined with geo-technical borehole testing, enhance their reliability and cover large areas in a cost-effective way in comparison with the standard borehole tests. In Nafplion area, evidence was found for a low factor of safety against liquefaction at specific sites within the study area. The results show that liquefaction probability can reach 80% at some sites depending on selected earthquake scenario, mainly at depths between 5 and 10 meters. This should be considered as highly important information for making risk-based design decision in this region.

Key words: *seismic techniques, faults detection, liquefaction.*

1. Introduction

The urban planning of many cities is usually based on economic and social factors, without taking always into account the local geology and the active geodynamic processes. The problems emerg-

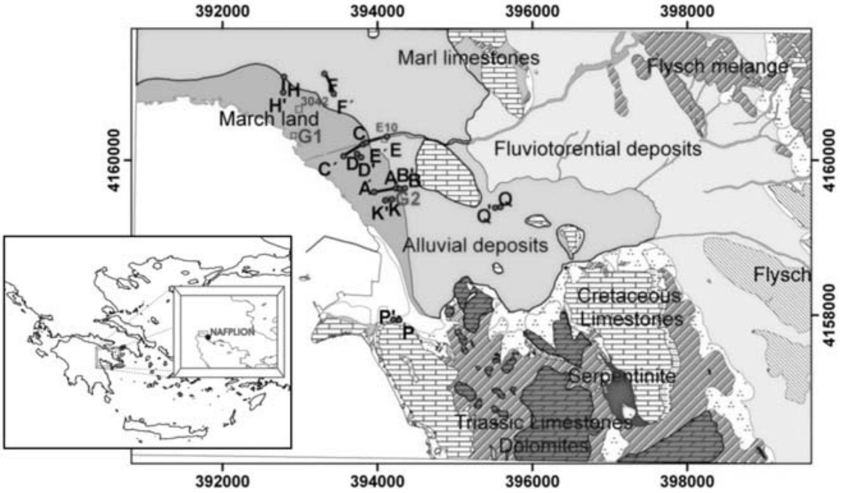

Fig. 1: Geological map of the investigated area. The seismic lines are presented with black colour. The boreholes are indicated with red coloured points. The embedded map shows the survey area (small box) close to Nafplion city.

ing due to this constraint are accentuated with the increase of the population, the industrialization and the seismic impact during the last decades. Nafplion is one of these cities (see Fig. 1), originally founded on safe ground, but it is expanding in recent years along the coastline on ground of questionable safety factor with reference to seismic and liquefaction risk.

The need to set up and test a methodology, able to give reliable evaluation of the seismic and liquefaction risk for extensive areas, is considerable, especially for the countries with high seismicity, like Greece.

The methodology followed, combined the usual borehole testing measurements of the standard regulation for the seismic and liquefaction risk with geophysical measurements, in order to spread out high credibility information to wider areas. The geophysical techniques also aided to the detection and study of the local active faults. According to the legal framework of many countries, the regular building is hindered in the adjacent to active faults areas. Similar restrictions apply to soils liable to liquefaction during a strong earthquake, to areas with slope stability problems, or to unconsolidated embankments etc. (EAK, 2000 - Greek Earthquake Design Code). Therefore, building can be allowed only if these factors are excluded. However exceptions are also possible, in special cases, after conducting special studies on the assessment and dealing with these particular risks. The gravity survey, as a reconnaissance method, is suitable to locate possible deformations of the bedrock, which can be attributed to faults. As a follow-up survey, seismic depth imaging can delineate the structure if this is related to an active or inactive fault. In the case of active faults, the dip and the total throw are usually examined.

The procedure for liquefaction assessment included the calculation of the Factor of Safety (FS) against liquefaction and the potential of liquefaction in terms of probability, (where FS = cyclic shear stress required to cause liquefaction / equivalent cyclic shear stress induced by earthquake), the evaluation of liquefaction time history for specific historical earthquakes scenarios and the analysis of site response in region of Nafplion taking into account the liquefaction susceptibility of the stratum.

2. Geological setting

The regional geology of the Argos plain is composed of: Coastal deposits, made of loose, fine silty sands and silty-clayey soils, alluvial fans and fluviotorrential deposits. The sediments' bedrock includes alpine and post-alpine sediments, such as flysch, limestone and Neogene marl conglomerates. The investigation area (see the geological map of Figure 1) is formed by alluvial, mainly lagoonal deposits, overlying flysch and limestone formations.

With regards to groundwater regime, within the Quaternary deposits, successive groundwater aquifers are developed, being under intensive exploitation by well boring. This resulted to a considerable sea water intrusion in recent years. Within some parts of the investigation area, at an altitude lying of a few meters above sea level, a weak unconfined coastal aquifer is developed at a small depth near surface, which is underlain by deeper confined aquifers. This shallow unconfined aquifer belongs to a local marshland. The sand-silty, clayey-silty nature of soils and the presence of the ground water table near the surface, constitute a particularly unfavourable regime concerning the foundations. Within this regime an attentive control of the liquefaction potential is pertinent.

In the Argos plain, where Nafplion is situated, a liquefaction has been recorded in the past, happened on 2/6/1898 and caused from an earthquake of M=7 with epicentre (37.6°, 22.5°) only 27 km far (NWW) from Nafplion (Ambraseys and Jackson, 1990, Papathanassiou et al., 2005). Three important seismic zones in the wider region of Nafplion have given strong earthquakes in the historic era (Iria fault, Epidaurus fault and Xylokastro fault) (Papazachos and Papazachou, 2003).

3. Geophysical investigations

The geophysical techniques were carried out in the area aiming at: a) the detection of possible local seismic faults and b) the determination of the velocity models in order to contribute to the estimation of the amplification of the possible peak ground acceleration (PGA) in the study area and the evaluation of the Factor of Safety against Liquefaction.

3.1. Geophysical investigations for mapping the bedrock relief and detection of possible faults

Gravity survey

The gravity survey covered an area of 35 km^2 with 270 stations, conducted with a Scintrex CG-5 gravity meter. From the Bouguer map a residual map was extracted (Fig. 2). Two major lineaments (see Fig. 2) can be seen possibly attributed to faults: The first one lies at the eastern side of the area with NW-SE direction. This is a known fault that has been mapped in the past from geologists as an inactive one. The second one, at the western part of the map, runs through the investigation area. Further investigation work with seismic methods was considered necessary.

Seismic Survey

A seismic survey was conducted to delineate the suspected fault as pointed out from the gravity survey. Each of the seismic profiles (see Fig. 1) AA′, CC′, EE′, FF′ was about 300 m long. The line HH′ was 180 m long. The main target of the seismic profiles was the determination of the dip of the bedrock surface and whether this could be associated to an active fault plane.

The survey layout for the shallow reflection seismics mostly used, was the "fixed spread" instead of the usual "roll-along". The "fixed spread" layout was not only easier in acquisition, in the case

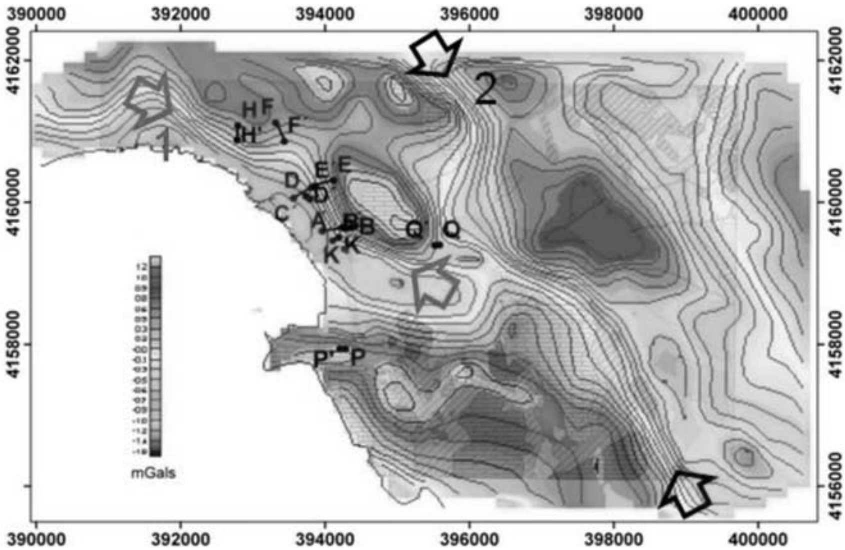

Fig. 2: The residual gravity anomaly map indicates the existence of two possible faults at the investigation area.

of urban environment, but was also very valuable since permitted the acquisition of data usable for refraction – wide angle reflection velocity modelling. A reliable velocity model is needed for depth migrating seismic data. We must bear in mind that if a fault is present in a seismic profile, then migration is a prerequisite.

The seismic source utilized, was an accelerated dropping weight and provided us with high quality records in all the seismic lines.

The joined lines EE′ and CC′ run perpendicular to the strike of the gravity lineament.

The first arrivals of the refracted waves in both profiles after tomographic processing, did not succeed to reach the bedrock. However the arrivals of reflected waves were processed by Zelt and Smith (1992) code, and produced velocity models with excellent fitting between calculated and observed arrival times (Fig. 3a). The resulted velocity models (Fig. 3b) indicate a fairly smooth layering to the bedrock. The bedrock is detected at 90 m depth at the beginning of the line EE′, reaching the 200 m at the end of CC′. The results are in agreement with an old water-wall at the starting edge of EE′, which intersected the limestone bedrock at 93 m depth.

Two layers can be distinguished above the bedrock at line CC′. The second layer, probably flysh, pinches out within the line EE′, but this cannot be resolved due to the limitation of vertical resolution.

Figure 4a shows the joined time migrated profile with simple depth conversion. Figures 4b,c show the resulted profiles after Kirchhoff depth migration with the use of the velocity model of the Figure 3b. The slope of the bedrock surface is steeper at the depth migrated profile.

The results of the depth migration (Fig. 4b,c) of the EE′ and CC′ lines suggest that the gravity lineament is caused by two smooth subsidence features of the bedrock at the starting parts of CC′ and EE′. Both dip values are at about 25^{o} and cannot suggest an active seismic fault. It is noted that apparent dips are measured and probably at a direction different of the bedrock gradient. Assuming that the strike of the gravity contour lines follow that of the slopping bedrock, the EE′ profile is at an

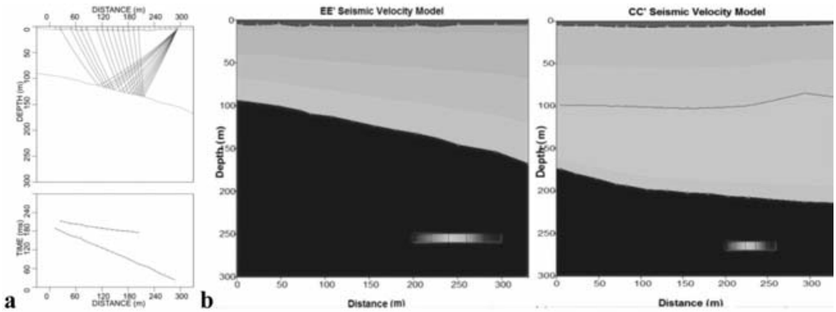

Fig. 3: Velocity modelling of the profiles EE′ and CC′.

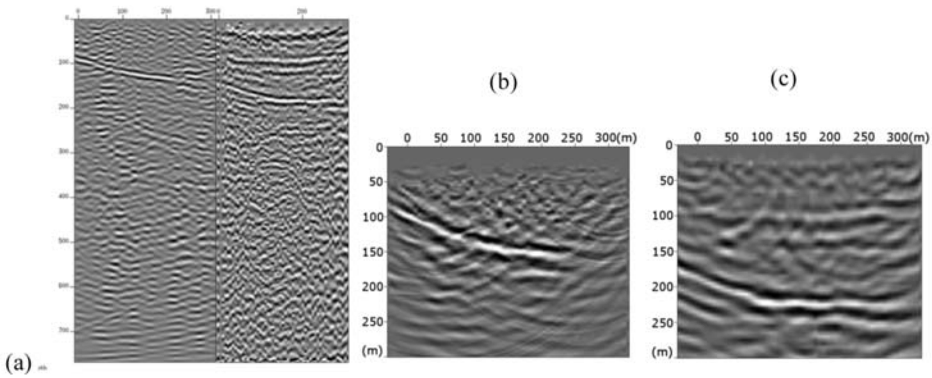

Fig. 4: a) Time migrated and depth converted joined seismic section of the profiles EE′and CC′ (b) and (c) Kirchhoff depth migrated profiles EE′ and CC′ respectively.

angle of 8° - 17° with this. The line CC′ is almost vertical to the gravity contour lines. Therefore after simple geometric calculations the real value of the dip up to 26°, can be estimated.

Similar dip values were also obtained in the AA′ profile after similar processing and calculations. The profile FF′ confirmed also the pinch out of flysh layer. Figure 5 shows also the results of HH′ processing in different stages. The results of HH′ are also in full accordance with these of the other profiles.

In conclusion, the linear features of the Bouguer map cannot be attributed to active seismic faults but only to small and low dip inactive faults.

3.2 Geophysical investigations to the characterization of foundation ground

Aiming to the assessment of the foundation ground, crosshole seismic tests were conducted at two sites within the study area, along with SPT testing and laboratory tests on borehole core samples.

In addition seismic surveys were jointly carried out between the boreholes in such a way to fill in with the adequate information. Figure 2 shows all the sites where the seismic surveys were conducted. At BB′, DD′, KK′, PP′, QQ′, the methods of seismic refraction of P and S waves, MASW (Xia et al. 1999) as well as microtremors analysis were applied. Additionally at the sites AA′, CC′,

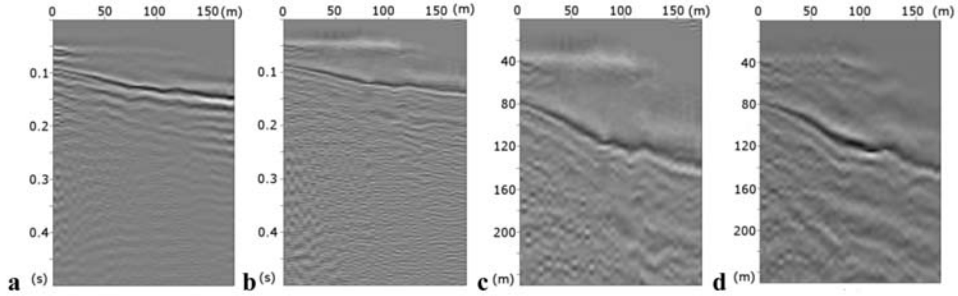

Fig. 5: a. Unmagrated stack section of the profile HH′ b. A section after deconvolution c. A deconvolved section after depth conversion d. Time migrated and depth converted section.

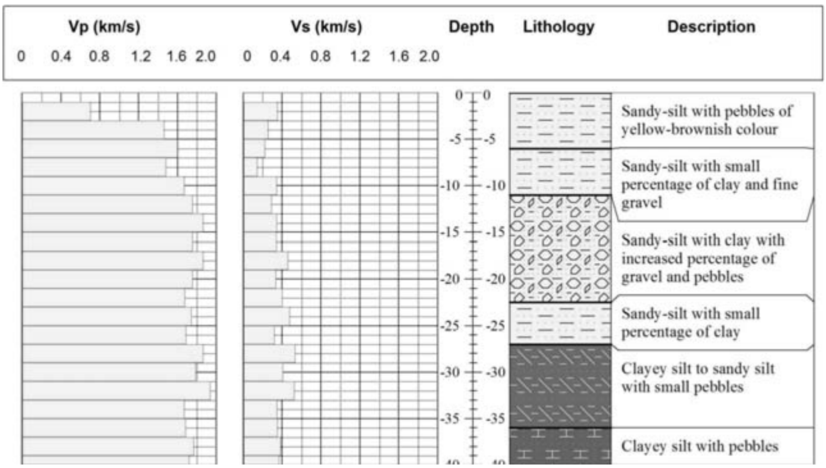

Fig. 6: Crosshole test results with the geological log.

EE′ and FF′ where seismic reflection and refraction data were acquired, MASW was also applied.

The seismic crosshole tests were conducted according to the ASTM D4428/D4428M-07 standard. At each site a pair of boreholes was drilled at 5 meters distance, at the depth of 40 meters. The results showed that the shear wave seismic velocity values in the loose sandy-silt and clayey silt intercalating formations did not exceed 0.4 km/s, but moreover there are parts with values lower than even 0.2 km/s. The P-wave velocity is high due to the saturation from the sea intrusion at the area. The results of the crosshole testing G2 and borehole log (Fig. 1) are presented in Fig. 6.

At the site of borehole G2 (Fig. 2) Reverse VSP (RVSP) modelling was also conducted with the seismic source in the borehole and the receivers at the surface. The results of tomographic algorithm (Hayashi and Takahashi, 2001) were excellent and it was found that the drilling of second hole could be spared.

Figure 7 shows the result of the RVSP modelling and a comparison diagram with the crosshole test. The crosshole testing and RVSP were also used to calibrate and validate the results of MASW.

The application of MASW gave satisfactory results and detected low S-wave velocity zones. In a

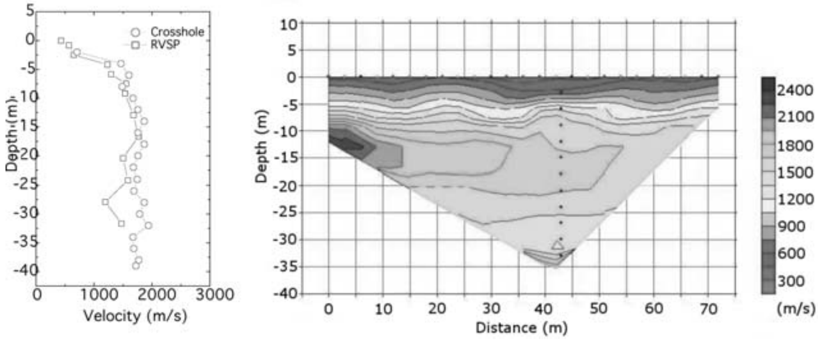

Fig. 7: Left: Comparison of RVSP (circles) with crosshole testing (squares). Right: The velocity model of RVSP at the site K.

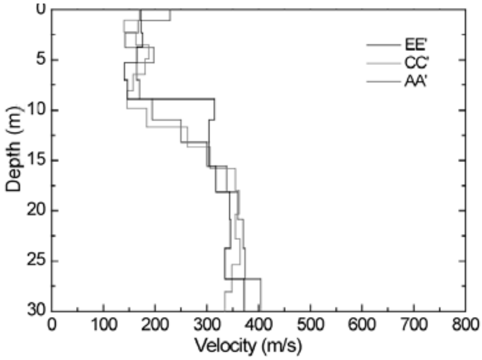

Fig. 8: MASW results systematically showed low S-wave velocity values at the first 10 m depth.

close distance to G2 borehole MASW was applied and the results were in full accordance to the crosshole test.

As shown in Figure 8 the S-wave velocity presents low velocities in the first 10 m in all investigated area. This is also found from S-wave seismic refraction profiles. Microtremors analysis also assisted to the description of the deeper S-wave velocity variation.

From information derived from the local boreholes the layer corresponding to the low S-wave velocity values is sandy-silt to silty-sand, soft formation without plasticity. The laboratory analysis found sand concentration of 29% and 66% at 4.90- 5.55 m and 7.90 - 8.55 m depth respectively. This evidence supports the high liquefaction risk.

4. Liquefaction analysis

The assessment of the liquefaction risk was based on the results of the seismic surveys, the geotechnical borehole testing and the stochastic simulation of strong ground motion for specific earthquake scenarios (Beresnev and Atkinson, 1997), selected based on the historical seismicity of this region.

The procedure consisted of the following steps:

1. Calculation of the Factor of Safety (FS) against liquefaction, and estimation of the potential for liquefaction in terms of probability (PL), based on factors of safety.
2. Evaluation of liquefaction time histories at the potentially liquefiable sites, using nonlinear,

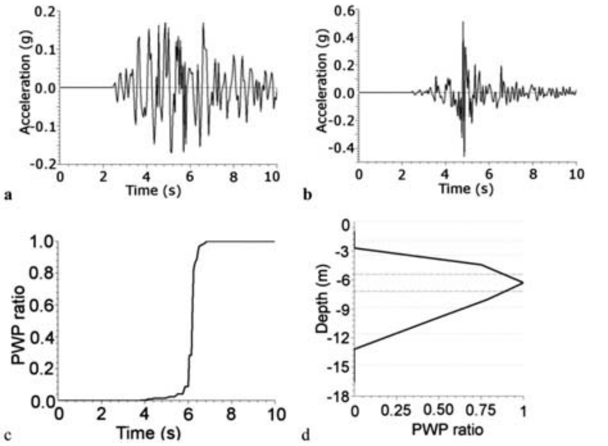

Fig. 9: Results of the liquefaction analysis for the AA′ test site of Nafplion: (a) surface acceleration time history; (b) the acceleration time history at the potentially liquefiable layer; (c) the time history and (d) the depth distribution of pore water pressure ratio.

effective stress site response analysis (Matasovic, 2006), capable of modelling pore water pressure generation and dissipation.

3. Analysis of seismic site response in the Nafplion area taking into account the liquefaction susceptibility of the ground depending on the earthquake scenarios.

The results of our analyses indicated the scenario of the activation of the Iria fault (Argos fault in Papazachos and Papazachou, 2003) as the worst one in terms of the liquefaction potential. The Epidaurus fault also showed similar characteristics in contrast to the Xylokastro fault that did not give high probability of liquefaction.

In the cases where high liquefaction potential was predicted, low values of PGA at the surface and seismic motion enriched in longer periods were observed. This was due to the fact that some layers, at depth, liquefied.

An example of this analysis is given for an M=6.4 hypothetical earthquake on the Iria fault in Fig. 9. Figure 9 shows (a) the surface acceleration time history (b) the acceleration time history at the potentially liquefiable layer, (c) the time history and (d) the depth distribution of pore water pressure ratio for the test site AA′. In the case of this earthquake scenario, liquefaction effect will prevent the effect of soil amplification. The ground acceleration at the surface level (Fig. 9a) has lower amplitudes and longer periods than the respective one below the liquefiable layer (Fig. 9b). This can be attributed, to the soil liquefaction occurrence to some extent at this site (Fig. 9c, d). For this earthquake scenario, the occurrence of liquefaction, in terms of probability, was high, reaching 86 % at depths between 6 to 10 m.

The discussion of the results of the site response analysis is not a subject of our present paper; however, the reader can find such detailed analysis in the paper of Karastathis et al. (2010).

5. Conclusions

The area where the Nafplion city is expanding, after its examination with realistic earthquake scenarios based on known earthquake sources associated with strong and catastrophic events in the recent past, can be considered as liable for liquefaction phenomena under certain conditions of seismic loading. The problem was mainly found at the depths of 8 to 10 meters, where a loose sand-silty layer is present with particularly low S-wave velocity values. The liquefaction potential was calculated, based on the results of the geotechnical investigations, laboratory tests and the results of the seismic surveys. A high liquefaction risk is anticipated mostly for strong earthquake scenarios at Iria and Epidaurus faults.

The study area was also examined for possible unexposed faults by a combined application of gravity and seismic methods but the results cannot support the presence of active faults.

The techniques utilized in Nafplion case, can also be applied with low cost in any other site with similar conditions as far as the liquefaction phenomenon is concerned. The view, that the geophysical techniques have already reached the required reliability to be included in the standard liquefaction risk studies, is well supported by the results.

6. Acknowledgments

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