Submarine Landslides and Local Tsunami Waves (Corinthos Gulf, Greece)

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It is considered a problem of submarine sediment slide which generates the surface water waves. To simulate numerically the landslide motion it is used the method which permits to take into account detailed rheological properties of slide body constituents. The numerical simulation of landslide-generated surface water waves is performed on the basis of nonlinear shallow water equations. It is studied a landslide behavior for two values of maximal friction angle. The detailed comparison of landslide dynamics and evolution of landslide-generated surface water waves during sliding is performed. Also, the evolution of dipolar water wave generated in the beginning of sediment sliding is studied. It is obtained that this dipolar wave is then transformed in two wave groups: crest and trough coming seaward and trough accompanied by crest coming to the shoreline. The second wave group leads firstly to sea recession from the beach and only then to large runup (tsunami wave with first negative phase).

Large water waves produced by submarine landslides were observed in many regions of the world for last 50 years (local tsunamis) (see, e.g. [1]). For numerical simulation of landslide-generated tsunami there were proposed a number of models, main of which are a rigid-body model and viscous (visco-plastic) model (for review, see, e.g. [2]). First model, because of its specifics, overestimates the water surface response to the submarine perturbation while second model underestimates it. To simulate adequately the landslide-induced tsunami it is necessary to use methods which take into account the both detailed structure of landslide body and mechanical characteristics of slide-body constituents during sliding (see, e.g. [3]). The character of disconsolidation of constituents in sediment surface layer appears to be a key factor which controls the localization process of the plastic strain and thus the slope instability. The model numerical simulation of sliding process at the continental slope was carried out for a number of slope parameters. In particular, such simulation of landslide induced tsunami was performed for parameters of Corinthos Gulf, Greece (see fig.1, 2) where in 7 February 1963 it was observed a damaging tsunami wave formed without any seismic events: mass of unconsolidated sediments slumped into the sea water around of the local river [4]. It is considered layer-by-layer sliding of upper part of elastically-plastic sediment layer on the slope surface which is formed during the landslide process. It is proposed a distinct interface between water and landslide body with water density \( \rho_w(x, z) = \text{const} \), and landslide density is a function of coordinate \( \rho_s = \rho_s(x, z) \) (see, fig.1). The coordinate origin is taken at the coastline, with \( x \)-axis at the undisturbed seawater level and directed seaward and with \( z \)-axis directed upward. In the fig.1 \( z = -h(x, t) \) is a variable depth of seawater, \( z = -h(x, 0) = -h_s(x, 0) \) is a submarine slide volume \( 57 \times 10^3 \text{m}^3 \) in Corinthos Gulf, (c) and equivalent to slumping volume \( 57 \times 10^3 \text{m}^3 \) in Corinthos Gulf, (b).

FIG. 1: Model scheme for simulation of tsunami wave generated by moving submarine landslide.

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\begin{align*}
\eta(x, t) &= \eta(x, 0) = 0, \quad \text{At simulation it was used explicit finite-difference scheme which permits to simulate the nonlinear behavior of pore saturated sediments under conditions of plastic flow above yield stress. Also, possible initial action at the process (adequate to some seismic action) was taken into account (see fig.2, where it is presented a geometrical scheme for numerical simulation of landslide (fig.2a) under the action of earthquake with moderate size magnitude (equivalent to slumping volume 57,000 m\(^3\) in Corinthos Gulf, fig.2b)).}
\end{align*}
\]

It was used a layered model of sediments rested on relatively rigid base. For each layer there were taken a layer density, shear modulus, bulk modulus, cohesion, maximal friction angle, and tensile strength. At the first stage, it was made the simulation of initial, preliminary stressed state of slope with sediments formed under action of its...
FIG. 2: a) Simulation scheme of submarine slope; upper layer is an elastically-plastic sediment mass rested on elastic base; b) Change of base velocity during earthquake with duration 6 sec and frequency 3 Hz; maximal velocity is equal to 0.2 m/sec corresponding to earthquake magnitude equal 6.

own weight and saturation with the water under sea pressure. At the second stage, it was taken into account the rheological effect of decrease sediment mass strength above yield stress, pore saturation of sediment mass and possibility of landslide-mass liquefaction under conditions of a seismic or any external action. And finally, it was performed numerical simulation of surface water waves (evolution and runup) on the basis of nonlinear system of shallow water equations with using of constructed explicit difference scheme with fulfilled stability conditions. Dynamical interaction between landslide motion and surface waves was taken into account via continuity equation. The results are consistent with those in conventional (rigid-body and viscous-fluid) model and agree qualitatively with natural data. So, it was really observed the sea recession (first negative tsunami wave) in the region of estuary of the local river in Corinthos Gulf, Greece where coastal strip have been slumped into the sea water (see above).

In the work there are presented results of numerical simulation for two values of maximal friction angle $\phi_s$: 20° and 32° (see below). In fig.3a, b there are presented a picture of successive position of landslide surface for several times with 10 sec interval (dashed curves) calculated for maximal friction angle $\phi_s$: 20° and 32°, respectively. Solid line corresponds to initial landslide shape ($t = 0$). At given values of parameters in the case $\phi_s = 20°$, landslide comes only finite distance, equal to 1200m. The duration of sliding process may be determined from the time instant when velocity of forefront reaches zero, and is near 50 sec. Maximal velocity of landslide forefront in this case is reached at near 40 sec and its value is near 6 m/sec. In contrast, rear part of the landslide shifts to lower x. In the case $\phi_s = 32°$, landslide comes only near 750 m (fig. 3b) and its maximal

FIG. 3: Evolution of submarine slope surface shape during landslide movement: a) $\phi_s = 20°$; b) $\phi_s = 32°$.

FIG. 4: Shear strain distribution at $\phi_s = 20°$ a) $t = 10$ sec; b) $t = 40$ sec.
velocity is essentially lower though it is reached also at near 40 sec.

In fig. 4a, b there are presented a shear strain distribution in landslide body for maximal friction angles \( \phi_s = 20^\circ \) for time 10 sec and 40 sec, respectively. From numerical results, it’s seen that in the case \( \phi_s = 20^\circ \) landslide forefront reaches level of horizontal bottom, and horizontal region near shoreline disappears so that landslide is plane up to shoreline. In the case of \( \phi_s = 32^\circ \) landslide don’t reach a horizontal bottom level so that landslide shape is plane only in the middle part of slope, and horizontal region near shoreline persists (see, \( \text{[1]} \)).

For numerical simulation of landslide-generated surface water waves it was used a system of shallow water nonlinear equations with taking into account the friction and Coriolis force

\[
\begin{align*}
\frac{\partial u}{\partial t} + uu_x + vv_x & = -g \frac{\partial \eta}{\partial x} - \frac{r}{H} u \sqrt{u^2 + v^2} + fu, \\
\frac{\partial v}{\partial t} + vv_x + uu_z & = -g \frac{\partial \eta}{\partial z} - \frac{r}{H} v \sqrt{u^2 + v^2} - fu,
\end{align*}
\]

where \( x, z \) are real space coordinates, \( t \) is the time, \( u(x,t), v(x,t) \) are velocity vector components, \( \eta \) is the surface elevation amplitude relative to undisturbed state, \( g \) is a gravity acceleration, \( H(x,t) = h(x,t) + \eta(x,t) \) is a total depth, \( (h) \) is a depth measured from undisturbed seawater level, \( r \) is a bed friction coefficient, \( f \) is a Coriolis force parameter.

Surface water waves were in fact generated by moving submarine landslide because of continuity equation in the form

\[
\frac{\partial (h + \eta)}{\partial t} = - \frac{\partial}{\partial x} ((h + \eta)u) - \frac{\partial}{\partial z} ((h + \eta)v) \quad (2)
\]

To solve the system numerically it was used a scheme constructed in analogy with those used in one-dimensional case. Numerical simulation process was based on splitting of difference operator: equations on \( x \) and \( z \) are integrated separately at two semi-steps in time. It was used a space dispersed pattern for different presentation of variables. To avoid the appearance of numerical instability problem and necessity to use a filtration scheme it was applied a method with first order in time scheme. The Cartesian coordinate system is taken so that total depth is positive in the region of liquid phase and is equal to zero at the phase interface \( (\eta = -h) \). So, negative values of \( H \) indicate to solid phase (beach). To localize the boundary it was used a linear extrapolation procedure. Since it is known that upstream oriented schemes are usually stable then it was used a conventional procedure for advective terms of equations of motion and continuity. The procedure is based on choosing of direction of space discretization.

In fig.5 it is presented an evolution of surface water waves (upper curves) generated by moving submarine landslide (lower curves) for the case of maximal friction angle \( \phi_s = 20^\circ \). The numbers near upper curves (surface waves) correspond to those near lower curves (position of landslide). There arise two distinct wave groups: crest and trough moving seaward, and second trough moving to a beach. It is seen that wave crest velocity is noticeably higher than that of landslide forefront. The picture is consistent with results of numerical simulation in conventional models (rigid body, viscous fluid, visco-plastic fluid).

In fig.6 there is presented an evolution of landslide-induced surface water waves corresponding to maximal friction angle \( \phi_s = 20^\circ \) with time step 10 seconds. In the beginning, it is generated a dipolar wave with trough oriented to a beach. This dipolar wave moves in the deep water direction. But soon an additional crest in the region of the trough appears which moves to a beach. Such recession of the sea water indeed was observed in the region where landslide occurs which phenomenon leads to anomalous tsunami with first negative phase \( 1 \) (depressive wave).

In conclusion, in contrast to kinematic method, complete solution of problem with stress strained state of slope at seismic action gives the possibility to estimate the distribution of residual strain and displacement in overall sediment volume with taking into account its possible liquefaction and disconsolidation \( 6 \). Numerical code FLAC, in contrast to finite element method realizes an explicit finite difference scheme for solution of three-dimensional (3D) problems in continuum mechanics that permits one to simulate nonlinear behavior of pore saturated mass under conditions of plastic flow above yield stress. For calculations, material
was divided to polyhedral elements in the limit of grid corresponding to shape of calculated object. Each element behaves itself according to action of applied forces and edge’s restrictions. The grid is frozen in material and moves together with it being undergone to finite strain and displacement. Explicit Lagrange scheme of calculations guarantees an accurate simulation and material flow. A key factor to control the process of localization of plastic strain and related instability is a character of constituents composing the surface sediment layer. The essence of this phenomena is that straining of real sediment layer after reaching of destruction point is continued at decreasing stress, i.e. it occurs decrease of limit of strength at increase of strain up to stress reaches some finite or residual level. Process of sediment mass sliding is essentially determined by friction angle. According to experiments, submarine sediments are disconsolidated when reaching maximal strength. Firstly, sediment mass is strained elastically but when limit condition $\tau = \tau_s = \sigma \cos \phi_s - \sigma \sin \phi_s$ is fulfilled it begins to move. In result, friction angle decreases from the peak value $\phi = \phi_s$ in the maximal strain point, and it is established a new equilibrium state at the level $\tau = \tau_k = \sigma \cos \phi_k - \sigma \sin \phi_k$ at residual value $\phi = \phi_k$. Moreover, strength decrease of sediment mass during the development of plastic strain at static action is a key factor to control a slope stability. In the case of neglecting of the effect of sediment mass strength decrease slope displacements remains to be small which fact leads to mistake conclusions. And for further agreement of numerical simulation results with natural data it is necessary to attract the detailed data about inner structure of sediment formations in landslide dangerous regions of slopes and landslide constituent properties.

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