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TSUNAMIS INDUCED BY SUBMARINE SLUMPINGS OFF THE COAST OF ISRAEL

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ABSTRACT

In the course of history several extreme changes in the sea level along the coast of the Levant have occurred. As these events have always been associated with earthquakes they were often described as tsunami or seismic sea waves.

Reviewing the historical descriptions of such events at Israel's coast, one finds more often a recession of the sea than a flooding of the shore. Such events may have been caused by slumpings on the continental slope. Based on data of actual submarine scars, a quantitative evaluation of this hypothesis was made.

It was found that the slumping of a mass 6 km long, 2 km wide and about 50 m deep would cause the formation of a shock-induced solitary wave of about 10 m in height at the edge of the continental slope. The accompanying draw-down of the sea level at the coast would last about $\frac{1}{2}$ - $1\frac{1}{2}$ hours, and lay the sea floor bare for a distance of about $\frac{1}{2}$ - $1\frac{1}{2}$ km, in agreement with some historical descriptions. Though possibly occurring only once or twice in a millennium, earthquake-induced slumpings may constitute a danger to nuclear power plants, and not just to maritime vessels and installations.

(*) This report represents the personal ideas of the authors and does not necessarily constitute the opinion of the Israel Atomic Energy Commission.

INTRODUCTION

Extreme and violent changes in the sea level at the coast of Israel in particular, and of the Levant in general, have occurred several times with disastrous consequences, and were therefore described in historical material. When planning important and costly installations at the coast, such as nuclear power stations, study of these phenomena is mandatory.

While "tidal waves" have mostly been mentioned in history in conjunction with earthquakes, and been thought to be true tsunamis, a more recent study (AMBRASEYS, 1962 a) suggested that submarine slumpings may be the cause of many such events on the eastern Mediterranean coast. One of our reasons for suspecting that not all events described are tectonically generated tsunami lies in the stress laid in historical descriptions on the recession of the sea, with little or no mention of an inundation of the land. Furthermore, the duration of such a recession seems much longer than would be expected for a true tsunami.

The purpose of this paper is to evaluate a model of such a mechanism quantitatively by applying it to data of the submarine slope and slumping niches off Israel's coast, and by comparing the results with available historical descriptions.

HISTORICAL DESCRIPTIONS

Lists of earthquakes in the Holy Land and in other regions in the Levant have often been made, and were recently summarized by WILLIS (1928), KALLNER-AMIRAN (1951) and AMBRASEYS (1962 a). Though the known primary sources are not very numerous and are dispersed in ancient literature and not readily accessible, chroniclers of the 18th and 19th centuries tended to copy from each other, introducing quite a few errors and these lists of earthquakes grew in length without firm foundation. AMBRASEYS (1962) went back to original sources and thus weeded out several errors. Since we are concerned primarily with the mechanism of these sea level changes, only a few examples of these occurrences will be cited, quoting from sources but without historical and bibliographical analysis.

— One of the earliest descriptions of an extreme change in sea level is given in the Bible by Amos (I, 1,2) who prophesied "in the days of Uzziah, King of Judah, and in the days of Jeroboam, son of Joash, King of Israel, two years before the earthquake" (about 760 BC), "and the desert springs withered and the Cape of the Carmel became dry" (literally : the "Rosh", Head of the Carmel; may be taken as "Cape" as in Arabic "Ras").

— In 23 ± 3 BC, a seismic sea wave, probably connected with the 26 BC earthquake in Cyprus [2] affected the Egyptian and the northern Sinai Coast, and was described by Strabo : "while we were in Alexandria in Egypt, the sea rose near Pelusium and Mount Cassius, invaded the land

and the mount became an island". (Mount Cassius is a 60 m high hillock on a lagoonar bar, normally several hundred metres wide).

— In 115 AD a large earthquake shook Syria and Palestine [36] and may have caused a sea wave affecting Yavneh and Caesarea. According to an analysis of old Jewish texts (SHALEM, 1956), this tsunami occurred on 13.12.115 and is said to have been noticed even as far as Rome.

— Many sources (see AMBRASEYS, 1962) describe the great earthquake which affected the Middle East from Palestine to Arabia and Mesopotamia on 9.7.551. The Syrian coast between Tyre and Tripoli, especially at Betrys (Beirut), suffered heavy damage. Theophanes relates that "the sea receded a thousand paces (1 mile), consequently many ships submerged in the deep". Michael the Syrian (as quoted by SHALEM, 1956) wrote that "at the time of the earthquake in Beirut and other Phoenician towns, the sea withdrew 2 miles and the sea bottom was exposed, laying bare sunken ships with much treasure. People ... ran down to the ships, but the sea waves returned, drowning all. Those at the shore fled to their houses, but the earthquake caused those to crumble and they were buried under ruins".

— During the winter of 1033/34 there were earthquakes in the Middle East lasting about 40 days [5] and as As-Soyuti (quoted in Ref. 3) noted, they took place in Egypt and Syria. The most destructive earthquake occurred on 5.12.1033 according to SHALEM (1956), or on 4.1.1034 according to AMBRASEYS. Abu El Faraj reported "half of Acre was destroyed, the sea receded 3 miles from the coast so that many, who walked out to collect things, were drowned when the waters powerfully returned". Yahia Ben Said of Antiochia (quoted verbatim in BRASLAWSKY, 1938) added that "the water within the port of Acre receded and disappeared for one hour".

— As-Soyuti [3] described the earthquake of 18.3.1068 : "An earthquake in Palestine, extending to Tabuk (in Hedjas) and as far as Kufa (Iraq). Ramle (then the local capital, *authors*) was destroyed, only 2 houses remained standing, 25 thousand persons perished. Was also felt in Jerusalem. The sea receded from the coast but soon returned to its place". Ibn El Athir gave a very similar description adding "the sea fled a day's walk" [30].

— Several medieval manuscripts (quoted verbatim in BRASLAWSKY, 1938) describe the earthquake of 14.1.1546, which is said to have destroyed Ramle, Nablus, possibly also Jaffa, and caused some memorable damage in Jerusalem. From two sources it is learned that "the sea at Jaffa receded a day's journey, one could walk on the dry bottom, and about 10 thousand people came to pick up things from the sea floor, however the sea returned soon and all drowned". Bernhertz (1616) [2] gave a similar description adding that the "sea bottom remained dry for three days".

— There was a severe earthquake causing widespread destruction in Palestine and southern Lebanon on 30.10.1759. Its epicentre is thought to have been at Safed. AMIRAN (1951) and AMBRASEYS (1962, a) note that Acre was also affected by a tidal wave, which flooded the streets to a height of 2 - 2½ metres. However several contemporary sources (researched by the authors) failed to mention the flooding of Acre in their descriptions of this earthquake.

In concluding the listing of historical descriptions of the effects of seismic tidal waves on the coast of Israel, one cannot but note the similarity in descriptions of the earthquakes of 1033, 1068 and 1546, which causes some doubt as to whether one original description is not rendered in slightly different versions for several dates.

THE CONTINENTAL SLOPE AND SLUMPINGS

The block diagram of the Israeli Mediterranean shelf and slope made by NEEV and NIR (1965) indicates that the edge of the shelf, just below the 100 m depth, widens only little, from 17 km off Tel-Aviv to 22 km off Ashqelon. The bottom of the continental slope however, widens considerably southwards, from 58 km to 85 km (at 1 000 m depth). On the slope, at about 400 m depth, a ledge is indicated parallel to the coast between Jaffa and Ashdod at about 30 km off shore. This ledge is about 4 km wide and culminates in a shallow rise of about twenty metres.

The general shape of the continental slope is as follows :

Depth	50 m	100 m	200 m	400 m	600 m	1 000 m
Distance (km) off Tel Aviv	8	14	18	25	30	50
Distance (km) off Ashqelon	11	18	24	30	33	85

Scars of slumpings on the continental slope are described and clearly seen in seismic profiles in NEEV *et al.* (1973). The scar, shown in Profile 96 A and considered to be seen also in Profile 90 A in extrapolated cross section, is about 2 km wide, at least 6 km long, and about 50 m deep. Its shoreside end must be closer to the shore than 28.5 km and it extends to at least 35 km off the coast. NEEV and ALMAGOR [25] considered adjacent gaps (Profile 90 A) also to be scars formed by downslope gravitational sliding of uppermost sedimentary material. The gradients involved are shown in Table I.

TABLE I

The surface gradients of the continental slope
(at Profile 96 A, in NEEV *et al.* (1973), containing the scar)

Depth range (m)	100-200	200-300	300-400	400-565	inside scar 600-700	740-900	900-1 000
Gradient	1/70	1/42	1/23	1/15	1/22	1/40	1/65

It is seen that the sea bottom becomes steeper as the scar is approached, and at the section just above the scar it is steepest (> 1/15). Inside the scar the slope has resumed the angle it had above the steepest section, about 1/22, possibly an angle of stability. Below the scar the gradient again becomes smaller. One might surmise that a slope with a gradient larger than 1/15 is inherently unstable and would slump at suitable triggering, for example by an earthquake.

GENERAL CHARACTERISTICS OF TSUNAMIS

Tsunamis, or seismic sea waves, also referred to as tidal waves, are water waves generated primarily by an impulsive submarine disturbance. They are generally characterized by long wavelengths (up to 200 km) and small waveheights ($\frac{1}{2}$ - 1 m) relative to the depth of the ocean. Tsunamis can propagate rapidly over large ocean distances without suffering appreciable dispersion and can hardly be detected by ships at sea, as the slope of the wave front is imperceptible.

While tsunamis are generally considered [34] to be generated by a shallow focus earthquake under the ocean which causes a vertical deformation of the sea floor [7, 8, 32], they may also be caused directly by a volcanic submarine eruption [27] or indirectly by large earthquakes triggering avalanches of material on steep underwater slopes [12, 13]. For an earthquake to cause an appreciable tsunami, IIDA (1963) found the magnitude M (Richter Scale) to be $M \geqslant 6.42 + 0.017D$, where D is the focal depth (in km), and WIEGEL (1964), quoting IIDA [15, 16], gave it as $M \geqslant 6.3 + 0.01D$.

It has been calculated that on the average the energy of tsunami waves is only about 1% of the energy released by the generating earthquake, and the maximum does not exceed 2% [32, 33, 37]. The energy of an average tsunami is of the order of 10^{22} ergs [16].

When approaching a shore the wave amplitude may grow considerably, due to shoaling, to focusing of the wave energy by refraction and by a resonance effect of a particular coastal configuration. Thus a tsunami upon reaching a populated coast may cause great destruction, as did the tsunami of the 15th June 1896, which struck the coast of Japan and took the lives of 27 thousand persons, totally destroying ten thousand houses [20].

Of the group of tsunami waves the highest wave is not necessarily the first; the maximum run-up usually occurs within the first seven waves [31]. A recent numerical simulation study of tsunamis [21], which assumed a two-dimensional, time dependent, non-linear viscous flow model, showed that the second and the third waves were the highest. The wave amplitude was found to increase fourfold as the waves shoaled up a 1/15 continental slope. A very flat and shallow coast will dissipate a relatively large amount of wave energy; thus MATUO (1934) found that a slope of 1/15 will cause a run-up 7 times as high as a flat slope of 1/500. A tsunami reaching the shore will both run up the beach and draw down water to expose the sea bottom. The two vertical changes in sea level are estimated (WIEGEL, 1970) to be about equal (at a constant slope of beach).

The period of a tsunami is of the order of a thousand seconds, usually 10-15 minutes. Since the wavelength is so large relative to the ocean depth, a tsunami moves as a shallow water wave with a velocity of $(gd)^{1/2}$, d denoting the ocean depth and g the gravitational acceleration. As the tsunami passes into shallow coastal waters its period is much less affected than its amplitude and length, the amplification of the wave height depending on the slope and the configuration of the shore.

LABORATORY SIMULATION

A laboratory simulation of the generation of irregular waves by submarine landslides and slumpings has been performed by WIEGEL [33] by allowing a block to fall vertically or to slide along a submerged inclined plane. The basic conclusions of this study are important in the discussion of the particular case to be evaluated. The surface waves produced by falling or sliding of submerged bodies are characterized by a crest, followed by a trough one to three times larger in amplitude than that of the first crest, and again followed by another crest. The magnitude of the wave amplitude was found to depend primarily upon the net potential energy of the falling object and on the water depth, rather than on the object's dimensions. The wave period, on the other hand, depended mainly on the dimensions of the falling object and did not vary considerably with changes in the potential energy of the body or with the water depth. When the body was sliding down a slope rather than falling vertically, the wave amplitude decreased and its period increased. The difference between the two extreme cases, i.e. vertical fall and sliding on the minimum possible slope, was that the period of the wave caused by the sliding body was about four times the period caused by the falling body. The wave amplitude caused by the sliding body was found to be one fourth of the wave amplitude caused by the falling body. The waves created in this manner were observed to be dispersive with increasing period and decreasing amplitude with distance from the source.

WIEGEL also noticed that when the relation between the length of a vertically falling body and the resulting wave period is extrapolated, there is an indication that underwater slumping of the order of one kilometre in length would generate waves with a period of 10 to 15 minutes. Because of their great length such waves would not disperse considerably, hence exhibiting the general features of a tsunami.

WIEGEL's model experiments also led to the conclusion that the wave energy generated ranged between a fraction of 1% to about 2% of the net potential energy of the falling or sliding body. It may be noted that the energy of the wave caused by the great Lituya Bay landslide [23] was of the order of 2% of the potential energy of the soil mass that slid, and that a nearby solitary wave about 70 m high and two smaller ones moved down the bay and out to sea. Revised calculations by WILSON *et al.* (1962) and by VAN DORN (1965) showed that the fraction that may be converted into tsunami energy is on the average less than 1% and has never exceeded about 2%.

In a laboratory simulation of waves induced by landslides, LAW and

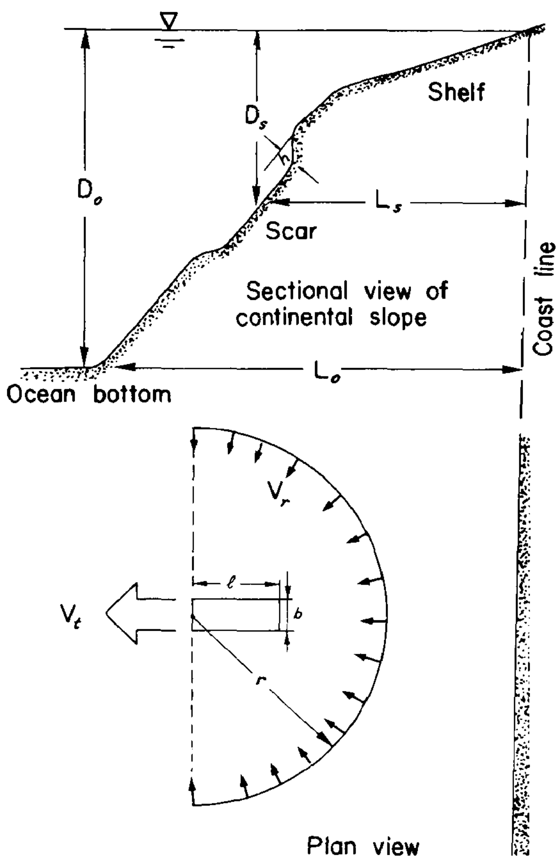
BREBNER (1968), using kinetic rather than potential energy, also found that at high kinetic energies there was a transfer ratio of about 2% between the kinetic energies of the waves and the landslide.

A QUANTITATIVE EVALUATION OF A TSUNAMI GENERATED BY SLUMPING OFF THE COAST OF ISRAEL

Let us assume a scar of breadth b, depth h and length l (Fig. 1) to form by a slumping on the continental slope. We denote the depth at the centre of gravity of the scar as D_s and its distance from the shore as L_s, the depth at the end of the continental slope as D_o at a distance L_o from the shore, ρ_s and ρ_w as the specific densities of the sea bottom material and sea water, respectively. The net (submerged) potential energy E_p, released by a slumping is then given by :

$$E_p = glbh(\rho_s - \rho_w)(D_o - D_s) \qquad (1)$$

g denoting the gravity acceleration.



According to WIEGEL (1964) the instantaneous disturbance of such a motion in water will usually generate a single solitary wave on the water surface. PRINS' (1958) laboratory experiments likewise indicated that a sudden change in the elevation of the water surface (which may be the result of a sudden change in the elevation at the bottom) caused one relatively large solitary wave together with a few smaller ones. The characteristics of the disturbance, its length l', its height h' at depth D, were found to determine the properties of the resulting surface waves. The relation between the ratios l'/D and h'/D caused the properties of the leading wave to range from oscillatory waves to a single bore [28]. Of particular interest is the range of l'/D and h'/D for which the resulting waves resemble a single solitary wave. PRINS' graphical data (also in WIEGEL, 1970, Fig. 11.5) suggest that this range is given by :

$$10 > 1.35(D/l')(h'/D)^{1.6} > 1 \tag{2}$$

The above relation is valid for two-dimensional wave propagation, ignoring lateral effects. Postulating that the gravity waves are generated by a sudden displacement of the bottom, it is possible to equate the parameters l' and h' with the length l and the depth h of the scar.

Let us assume that a displacement in the sea floor did generate a solitary surface wave, then the total energy E_w per unit width of crest of such a single wave is given by (Ref. 17, p. 125) :

$$E_w = \frac{g\rho_w}{8\sqrt{3}}(HD)^{3/2} \tag{3}$$

where H denotes the wave height and D the local water depth. To adapt to a three-dimensional problem let us assume that this wave energy is uniformly distributed over a finite width b, equated with the width of the scar. It is further assumed that a fraction μ ($\mu \ll 1$) of the potential energy E_p released by the slumping is actually transformed into wave energy. The height H of the generated wave is derived from equations (1) and (3) :

$$H = \frac{1}{D}\{8\sqrt{3}\,\mu l h(\delta - 1)(D_o - D_s)\}^{2/3} \tag{4}$$

where δ is the ratio between the specific gravities of sand and water, and providing $D_s \leqslant D \leqslant D_o$.

In order to estimate the period of the wave generated we assume that the wave exhibits some oscillatory behavior and use the general expression for the total wave energy per unit width :

$$E_w = g\rho_w \frac{H^2\lambda}{8} \tag{5}$$

where λ denotes the wave length, which in turn is related, in deep water, to the wave period T by :

$$\lambda = \frac{gT^2}{2\pi} \tag{6}$$

In his experiments WIEGEL (1955) found a satisfactory correlation between the energy of the falling object, the wave height and the periods generated and the calculated values, especially for relatively large potential energies. Adopting the basic reasoning but considering the resulting waves to be shallow water waves, in view of the conditions at our coast, we consider that equation (5) still applies but equation (6) should be replaced by :

$$\lambda = T(gD)^{1/2} \tag{7}$$

which is valid for shallow water. Substituting equations (4) and (7) into (3) and (5) yields the following expression for the wave period :

$$T = \frac{1}{2}(D^3/g)^{1/2}\{9\,\mu l h(\delta - 1)(D_o - D_s)\}^{-1/3} \tag{8}$$

Equations (4) and (8) are the expressions for the height and period of a slumping-induced wave disturbance, as functions of known parameters. The equations were derived on the assumption that the energy transmitted is contained in a single solitary wave. If one assumes that the wave energy is distributed evenly among m identical solitary waves, the resulting wave height H_m and period T_m would be :

$$H_m = H\,m^{-2/3}\,;T_m = T\,m^{1/3} \quad m = 2\,,3\,,4\,... \tag{9}$$

where H and T are given by equations (4) and (8) respectively.

We apply these considerations to the particular case off the coast of Israel described earlier, where the dimensions of the scar are $l = 6\times10^3$ m, $b = 2\times10^3$ m and $h = 50$ m. The location on the continental slope is given by $D_s = 650$ m and the depth of the ocean floor is $D_o = 1050$ m. We obtain $5.7 < l/D < 9.2$ and $0.048 < h/D < 0.077$ for $D_s \leqslant D \leqslant D_o$. These values compared with those of PRINS [28] fall within the range given by equation (2), thus justifying our assumption regarding the generation of a single solitary wave.

Using the scar dimensions as given, and assuming $\rho_s = 2$ g/cm³, the potential energy of the slumping event according to equation (1) is $E_p = 2.4\times10^{22}$ erg, which if entirely converted into wave energy ($\mu = 1$) would cause a tsunami of 1.5 magnitude on the Iida Scale * [16]. Computing the height and the period by equations (4), (8) and (9) for generating a single ($m = 1$) or two equal solitary waves ($m = 2$), and taking $\delta = 2$ and a transformation factor of 1% ($\mu = 0.01$), we consider $D = D_s$ and $D = D_o$ to give upper and lower bounds of numerical results, as summarized in Table II.

TABLE II

Solitary wave heights and periods from a particular slumping event

	$m = 1$		$m = 2$	
Depth	D_s	D_o	D_s	D_o
H (m)	13	8	8	5
T (sec)	700	1 400	900	1 850

These values of wave height and period were derived assuming vertical

* On this scale the magnitude of the tsunami is approximately equal to the logarithm to base 2 of the run-up measured in metres.

travel of the slumping mass. However, in fact, the mass did slide on a moderate slope, and so the results of WIEGEL's (1955) laboratory experiments should be applied, i.e. the period of a slide-induced wave was about four times the period of a fall-induced wave for the same potential energy, with a compensating reduction in the wave height. While in WIEGEL's model the total energy was proportional to H^2T^2 (deep water), in our evaluation using shallow water waves the total energy is proportional to H^2T. Hence if we assume the period to increase by a factor of four for our case of a sliding mass, the wave height would decrease only by a factor of two. (The alternative, namely the assumption that the wave height is reduced by a factor of four and the period increased by a factor of sixteen, seems unrealistic). Counteracting this reduction in wave height of waves approaching the shore would be the shoaling effect, considerable for the large wave length involved. Under ideal conditions the shoaling effect may be given by Green's Law [17] :

$$\frac{H_1}{H_2} = \left(\frac{D_2}{D_1}\right)^{1/4} \tag{10}$$

where the subscripts 1 and 2 denote shallow and deep water, respectively. The wave height over the continental shelf nearer the shore, (D_1 = 25 m to 75 m), would therefore increase by a factor of about 2 or even more, closer to the shore. Further assuming the wave power to be constant, i.e. disregarding friction loss, wave refraction and reflection, we derive, from continuity arguments, that the wave period will not vary effectively as the wave moves into shallow water, the change being distributed between wave height, length and velocity.

Bearing in mind that the slumping will primarily cause an impulse in the seaward direction, the main features will be seaward propagation of a wave, or waves, and a shoreward propagation of a trough. From the aforegoing evaluation one might expect the net effect of the flat sliding, on one hand, and the shoaling, on the other hand, to be about a fourfold increase in the wave-period as given in Table II with no significant change in the wave height.

Thus the wave period would be about 1-1½ hours, and the draw-down about 10 m, or more, near the shore, laying bare about one kilometre of sea bottom. It is believed that these relatively large wave periods, when applied to the recession of the sea, are rather conservative estimates, since it was found in WIEGEL's (1955) experiments that the amplitude at the trough was one to three times larger than the amplitude of the crest. It was also found that due to dissipation effects the period increased (wave height increasing) with increasing distance from the source. These two effects, which tend to increase the duration of the sea recession even more, were not considered in this analysis.

The evaluation so far had been based on the assumption that only 1% (μ = 0.01) of the total potential energy was imparted to the gravity waves. Assuming however that 2% (μ = 0.02) would become effective, the wave height would increase by a factor of 1.6, whereas the wave period would decrease by a factor of 1.3 only. These factors when applied to the results in Table II will not change the order of magnitude of the calculated values.

In an earthquake-induced tsunami the source sends waves towards the coast and the major effect is an inundation. Since a slumping-induced wave is a sea-going wave (BASCOM, 1964) the predominant effect felt at the shore is a draw-down or a recession of the sea. The subsequent run-up, if any, will probably not be considerable, since most of the energy has dissipated seawards. Observational or experimental data on run-up, such as in ADAMS (1969) or the summary of the theoretical treatment by WIEGEL (1964), are not good guides for hypothesing in our case, where the primary phenomenon is a draw-down. Following WIEGEL (1970, p. 286) we shall meanwhile postulate the shoreward draw-down of the sea-going wave to be of the order of the wave height, as measured on a tide gauge, usually located a short distance offshore.

DISCUSSION

The model proposed here is based on a preliminary and approximate evaluation, and it is hoped that a more rigorous mathematical treatment will substantiate the findings. We also tried to check our results by taking a different set of assumptions. While the main evaluation was based on the potential energy of the slumping mass causing one or two solitary waves, we might have proceeded by assuming the slumping mass to be in effect a high density and high velocity turbidity current, similar to the model of HEEZEN and EWING (1952), as follows.

Denoting the velocity of the turbidity current by V_t and assuming that the sand contained in the scar was carried away in suspension with the same velocity, the total kinetic energy of the moving slump would be :

$$E_k = \frac{1}{2}\rho_s l b h\, V_t^2 \tag{11}$$

In order to assess the duration of the seaward motion imparted to the surrounding water it was further assumed that the slumping mass was discharged with uniform velocity V_t through the scar aperture area bh. The time t_1 required to drain the scar could thus be approximated by :

$$t_1 \doteq l/V_t \tag{12}$$

The additional time, t_2, required for the slumping mass to come to rest at the end of the continental slope, at a depth D_o, is approximated by :

$$t_2 \doteq \frac{L_o - L_s}{V_t} \tag{13}$$

assuming that the average gradient of the continental slope is small. The total duration of the slumping event may thus be $t_1 + t_2$, which, in conjunction with equation (11) implies that the average power of the slumping is approximately given by :

$$P_k = \frac{E_k}{t_1 + t_2} = \frac{1}{2} \quad \frac{\rho_s l b h\, V_t^3}{l + L_o - L_s} \tag{14}$$

Only a fraction of this value μP_k would be transformed into oscillatory wave power P_w, which is given by (Ref. 35, p. 286) :

$$P_w = \frac{1}{8} g \rho_w H^2 C_G \quad (15)$$

per unit crest width, where C_G is the wave group velocity, rendered for shallow water waves as :

$$C_G = (gD)^{1/2} \quad (16)$$

Again assuming that the wave power is evenly distributed over the wave crest, which equals the scar width b, and combining equations (14), (15) and (16) we obtain the following expression for the wave height :

$$H = \frac{2 V_t^2}{g} \left\{ \frac{lh}{V_t} \left(\frac{g}{D} \right)^{1/2} \frac{\mu \delta}{l + L_o - L_s} \right\}^{1/2} \quad (17)$$

According to HEEZEN (1963, p. 744) the turbidity current down a 0.03-0.1 slope may reach a velocity $V_t = 30$ m/sec. Using the same values as before to compute the wave height, equation (17) yields $H = 13$ m for $D = D_s$ and $H = 11.6$ m for $D = D_o$, for a single wave.

It can be seen that two rather independent evaluations, i.e. one based on the "solitary wave-energy" approach and the other on the "turbidity current-momentum" idea yield very similar results for the wave height and the period, supporting our previous results.

This model can be used to assess the lateral extent of the effects of a slumping event. We assume a simple two-dimensional steady state model, in which the turbidity current exits with a velocity V_t from an opening (the scar), having a width equal to b. To satisfy continuity the discharge through the opening is deemed to be compensated by a seaward radial flow through a semi-circle, lying shoreward and whose center coincides with the center of the opening (fig. 1). Neglecting any dependence on the local water depth, the velocity V_r, induced at a radial distance r from the centre of the opening, would be :

$$V_r = \frac{b V_t}{\pi r} \quad (18)$$

The radial distance at which the induced velocity would be equal to that of the normal offshore current, i.e. 0.5 m/sec [11], would be about 40 km for $V_t = 30$ m/sec and $b = 2 \times 10^3$ m. As the scar is about 30 km from the shore, off Nahal Evtah half way between Ashdod and Ashqelon, this slumping may have been felt along a coastal stretch of about 55 km, though of course the central part would show the most spectacular effects, especially the recession of the sea.

The dimensions of the scar used in the evaluation must not be considered as extreme values: widths up to 2.7 km and depths up to 65 m have been recorded, although no length longer than 6 km has so far been established. Thus the energy input assumed here seems to be realistic, if not conservative, and not exaggerated.

Off the coast between Ashdod and Ashqelon there are four trench-like niches in a longshore profile, which might be considered as remnants of slumpings. Until the bottom sediments are studied, and even then, it may not be possible to tie these scars to specific historical descriptions. However at least on this stretch of the coast, further slumpings may be expected. Such events may be triggered, though not necessarily caused, by strong earthquakes from some distant tectonic structure such as the Jordan Rift Valley, a weak tremor from a nearby focus, such as the Palmahim Graben [25], or from other earthquakes at foci in the eastern Mediterranean.

The draw-down evaluated here to be ten to fifteen metres, or even more, would lay bare about one km of sea bottom at the southern coast and even a larger distance in the bay of Acre port, well in accord with the historical descriptions of one to two miles. The only duration specifically mentioned is one hour (the 1033/34 A.D. event), in good agreement with our estimate. While realizing the catastrophic effects of a slumping at a coast in maritime and industrial use, we do not think, on the strength of the historical evidence so far available, that such events did occur at Israel's southern coast more often than once or twice in a millennium. Their recurrence, however, depends on various factors, and perhaps mainly on the frequency of triggering earthquakes, and we cannot, at this stage, evaluate the risk of such events.

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