1. Introduction

First introduced, the braking of the tsunami waves on the very shallow and plain shore during Asian tsunami 2004 on the coast of Africa Horn in city Xaafuun. In these optimal conditions the event of the tsunami serial waves is important for the understanding of the tsunami shoaling theory. This tsunami shoaling process has very well documented and afterwards verified with modern measuring tools.

Second presented, in details the shoaling theory for the breaking of the long-distance tsunami on the very shallow and plain shore. This shoaling theory combines Green's wave theory [1] with the dam wall break theory [7] and describes the whole tsunami shoaling process on the very shallow shore.

Third described, how the single tsunami wave breaks on the deeper water and is flowing over the still seawater to the shoreline. The broken tsunami wave on the sea surface takes a big amount of seawater with in flowing to the shoreline and makes many meters thick tsunami bore to the shore.

Fourth explained, why the tsunami wave is minimal in the very deep and steep shore without the bore. The tsunami wave on the open ocean will not brake and has no reinforcing effect of the seawater drawback. This phenomenon is very general in the deep and steep shores as in Asia and in Japan.

Fifth described, how the tsunami bore flows upwards along the river, which is at the sea level. The shoaling theory explain, why the height of the bore in the river surface is rising so huge with the serial waves.

Sixth presented, how the tsunami will be dampened nearshore by utilizing the friction and mixing of the seawater flows after the tsunami wave's break in the shallow bathymetry conditions. If in the front of the coastline there is a shallow water, it is possible to build up the artificial shoreline, which dampen the tsunami. One natural damping example is the sandbanks in front of the city Faro in Portugal during the 1755 tsunami.

The presented shoaling theory of the tsunami wave explains in the simple way several seawater flow phenomena, which have observed during the tsunami shoaling process.

2. The wave breaking in Africa during Asian 2004 tsunami

Asian tsunami 2004 hit Somalian coast of Africa some 5000 km west of the earhtquake epicenter after 8 hours having average velocity over 600 km/h.

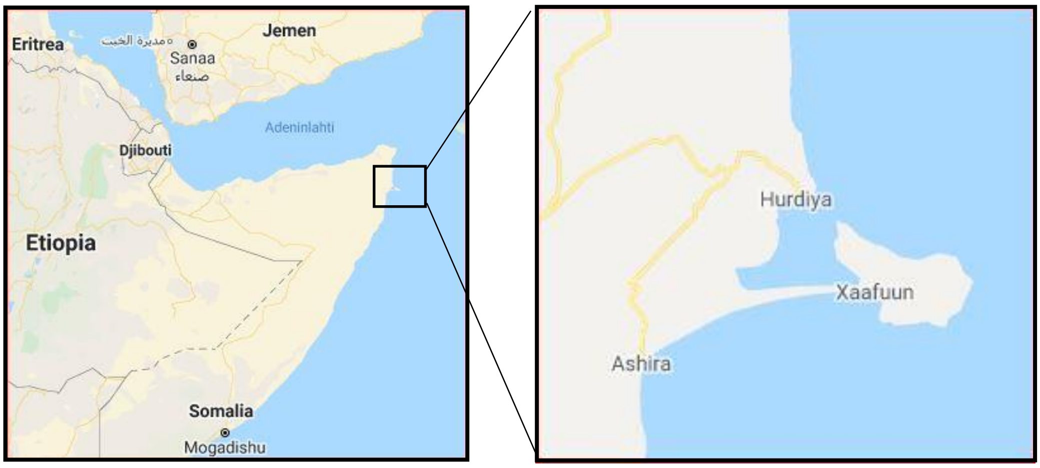

Fig 1. City Xaafuun in Africa Horn in Somalia

It is well documented in Somalian Field Survey [2] made by UNESCO. The Xaafuun Peninsula (Fig. 1) within Somalia juts out 40 km into the Indian Ocean, forming the easternmost point on the African continent.

City Xaafuun is believed to be the location of the ancient salt trade center, where is still left the pillars of the salt ropeway pier. The pillars of the pier helped to estimate the depth and length of three tsunami drawbacks. The ropeway extends 1500 m into the Indian Ocean

The local vice council was standing at the waterfront and waiting for the arrival of the Aasian 2004 tsunami. He gave a very detailed description of the initial wave sequence with the help of ropeway pillars [2]:

"At first, a 100 m drawback was noticed, followed by a first wave flooding to the beach. Next, the water withdrew again by 900 meter before the second wave partially flooded the town. Finally, the water withdrew again by 1300 m offshore before the third and most powerful wave washed through the town. These drawbacks correspond to 0.5 m, 4 m and 6 m depths" (Fig. 2).

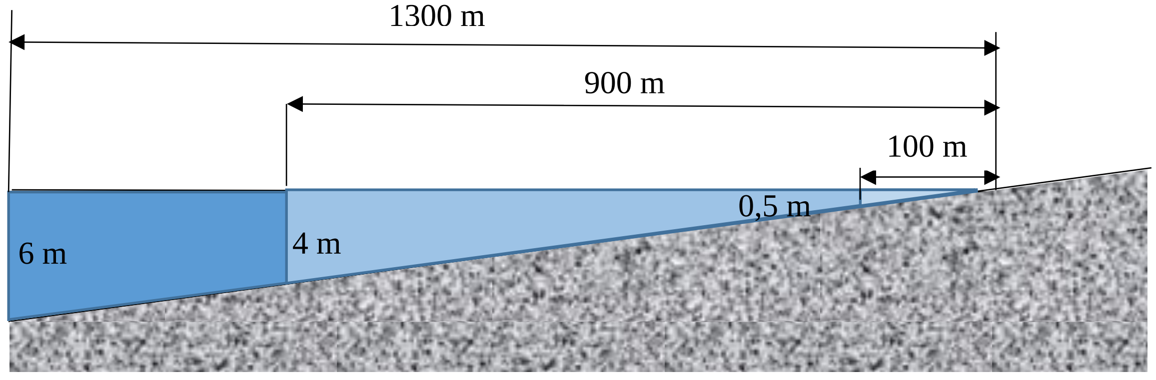

Fig. 2. Three drawbacks of the Asian 2004 tsunami in Xaafuun in Somalia

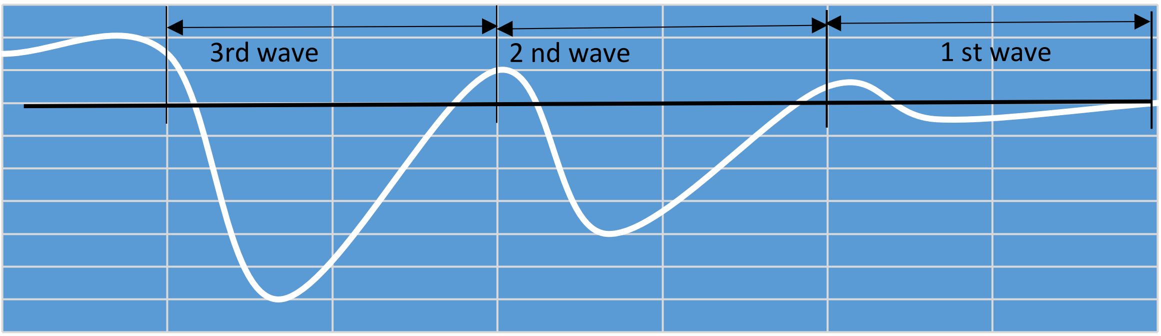

Fig. 3. Seawater level during the three drawbacks of the Asian 2004 tsunami in Xaafuun in Somalia

The estimated wave period was 12 minutes. It took roughly 2 min from the maximum drawback flow to the center of Xaafuun. The drawbacks took most of the time of the wave period and gave the shape for fluctuation on the seawater surface (Fig. 3).

Xaafuun was the only town on the coast, where a small initial drawback was observed because of the very shallow shore, which has the slope less than 0.5 %.

The drawback of the third wave was 1.3 km and the depth 6 m and the cross-section of the beach is shown (Fig 4). When taking a 1 m seawater slice perpendicular to the shoreline, the moving seawater is possible to calculate by the areas instead of the water volumes. The area of the third drawback is a triangle, having area A_1= 3900 m^2. If thought, that this water is on the seawater surface by the estimated depth of 1 meter, it makes 3.9 km length, having the same areas $A_2 = A_1$. In case of 2 meter depth the length is nearly 2 km.

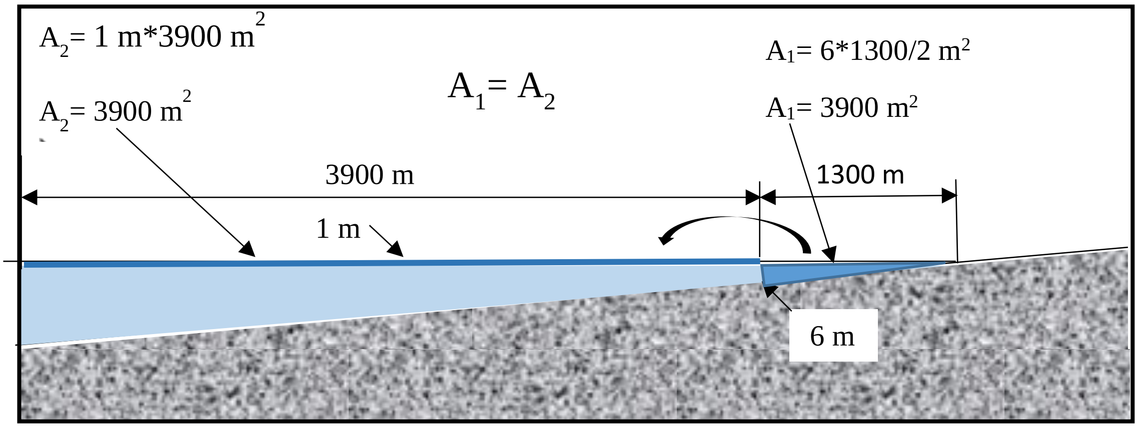

Fig 4. Cross-section of the beach before the 3rd wave in Xaafuun 2004

The important question is: How this drawback is possible, when tsunami wave is propagating to the opposite direction over 600 km/h on the open ocean?. Next section will give the theory of the tsunami shoaling on the shallow seawater.

3. Tsunami shoaling theory for shallow shore

When a kilometers-long tsunami wave approaches the coast, the amplitude of the tsunami wave will increase according to Green's law [2] depending on the depth of the seawater. Near the shoreline the rising tsunami wave sucks from the front seawater and seawater will withdraw. The sea bottom will open and we have a drawback phenomenon (Fig. 5).

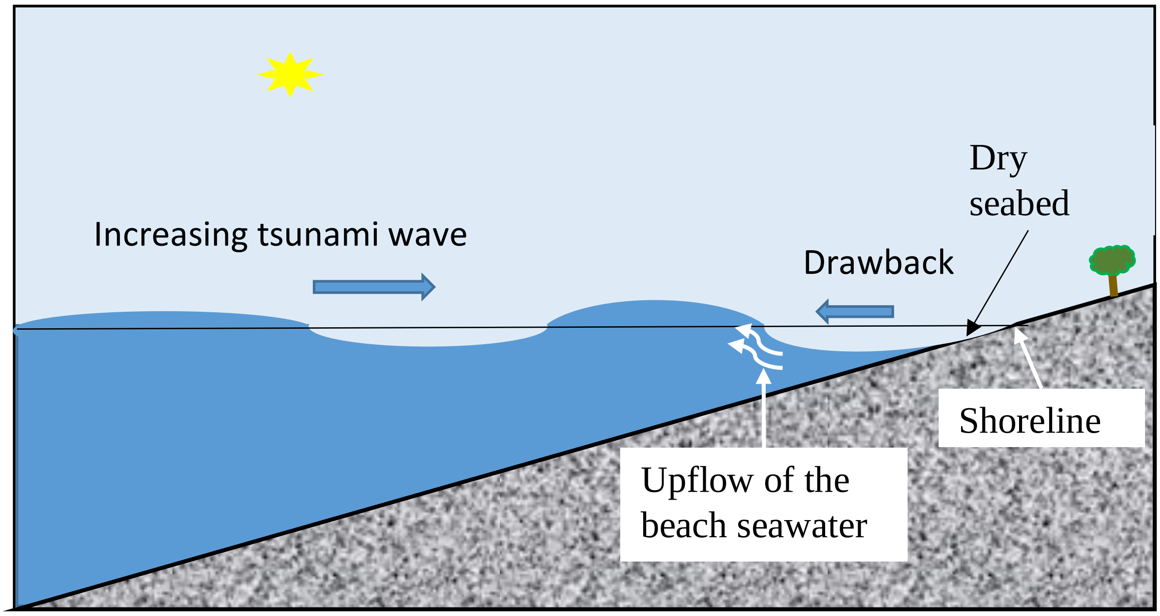

Fig. 5 Tsunami wave drawback and seawater rise

The velocity of the tsunami wave on the ocean is $U = \sqrt{d * g}$, where d is water depth and g gravity 9,81 m/s^2 ~10 m/s^2. In the depth of 1 km tsunami wave velocity is 100 m/s = 360 km/h, in the depth of 10 m tsunami wave velocity is only 10 m/s = 36 km/h (Fig 6). The gravity pressure of the tsunami wave has in 10 meter's depth 10 times more time to effect the water surface than in 1 kilometer's depth. A single seawater particle via pressure force F rises up 100 times higher in the depth of 10 m than 1 km. For example it means 1 cm wave height rises to 100 cm = 1m (Fig 6.).

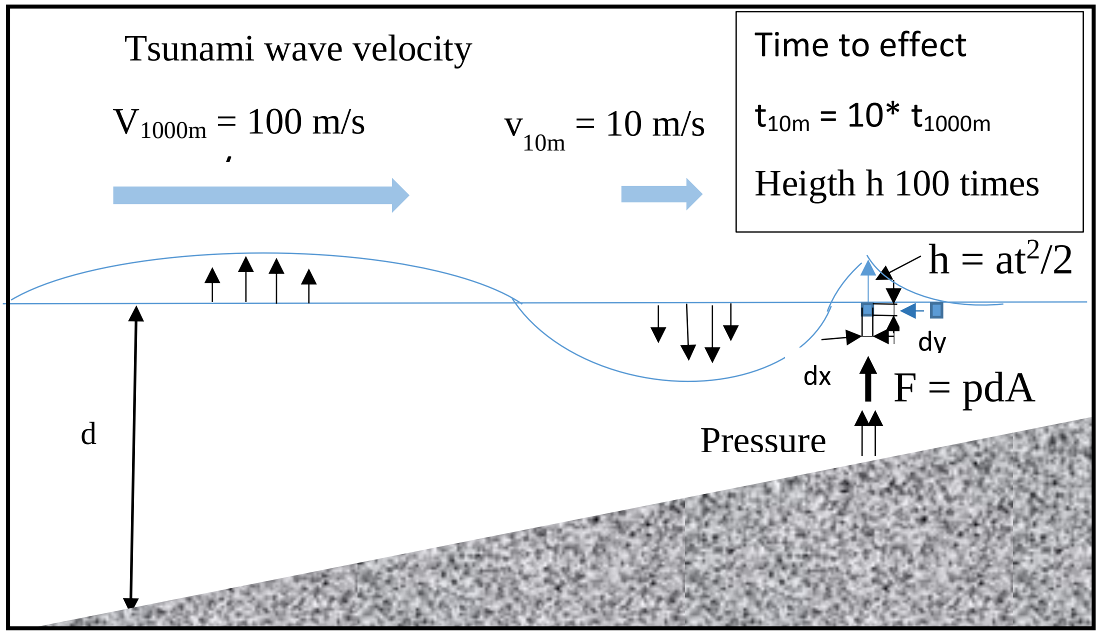

Fig. 6 Rise of seawater particle in lower tsunami wave velocity

On the open ocean in the depth of kilometers the seawater particle does not have time to rise due to the high velocity of the tsunami wave. This is the reason, why tsunami wave is difficult to see on the open ocean. On the other hand on the very shallow shore the tsunami wave begins always by the drawback of the seawater.

During the tsunami drawback seawater will flow to the open ocean and will hit to the edge of the kilometers-long tsunami wave. In the collision there will be a sharp drop of the seawater as in the waterfall (fig. 7). The breaking of the tsunami wave occurs.

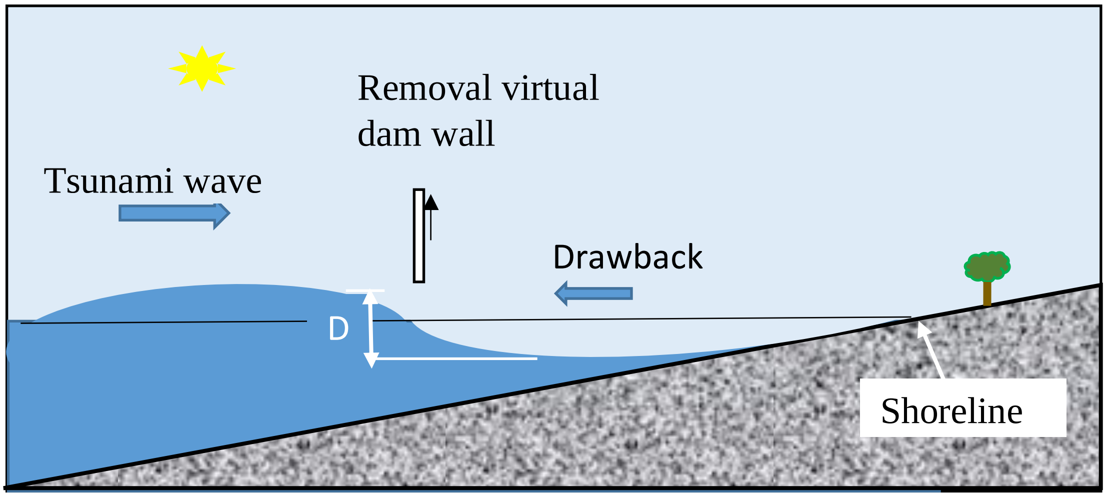

Fig 7. The collision of the tsunami drawback and wave

In this situation the water will behave like flow in the dam wall break. The water flows as a floodwater wave to the shore on the velocity V. According to dam break flow theory [3], [4], [5] the flow velocity (1) to the plain sloping shore is

$$V = 2 * \sqrt{D * g}, \qquad (1)$$

where V is flow velocity in m/s, D is the height of the total water drop in m and g gravity in m/s^2. If the total drop including height of the drawback and the tsunami is together D = 10 meter, the shoreward velocity on the sea in the breaking point is V= 20 m/s (72) km/h. The dry seabed will deaccelerate the born bore. According to the dam wall break theory there is negative wave (2) seawards with the velocity

$$\mathrm{Vn} = -\sqrt{D * g} \tag{2}$$

If we have D = 10 meter, negative wave velocity is Vn = -10 m/s (-36 km/h). During 2 minutes (120 sec) negative wave travels 1200 m (1.2 km) (Fig. 8).

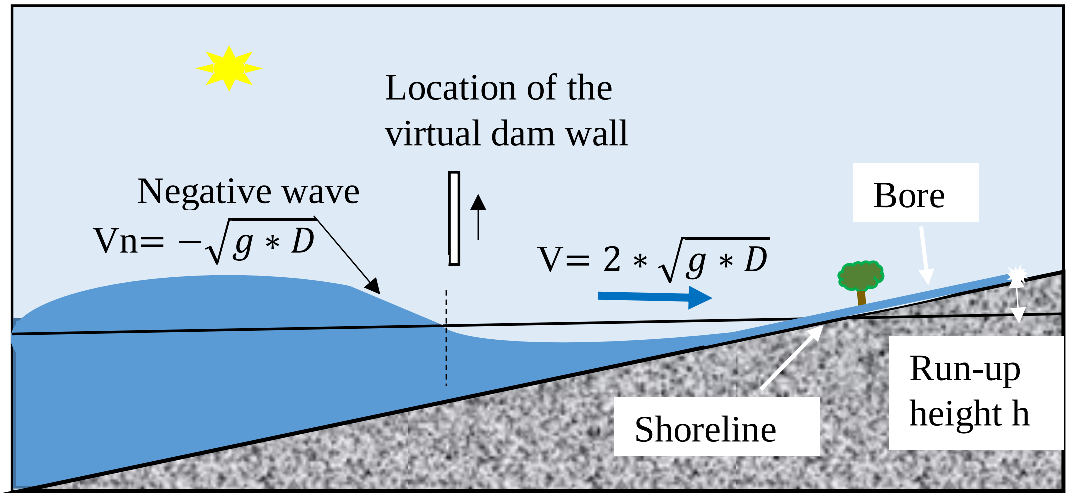

Fig. 8 Tsunami break wave flow, bore and run-up

According to the dam wall break theory [3],[4] it is possible to calculate the seawater flow profile, depth, velocity, volume flow, time and height of the run-up [7]. Tsunamis typically occur as a series of long period waves that break near the shoreline [8]. In addition it is possible to calculate the hydrostatic and hydrodynamic forces for onshore buildings [9], [10].

4. Tsunami shoaling theory for still seawater shore

When the seawater depth is less than 50 meters, the velocity of the approaching tsunami wave is slower and the wave starts to suck more water from the front by lifting the height of the tsunami wave (fig.9).

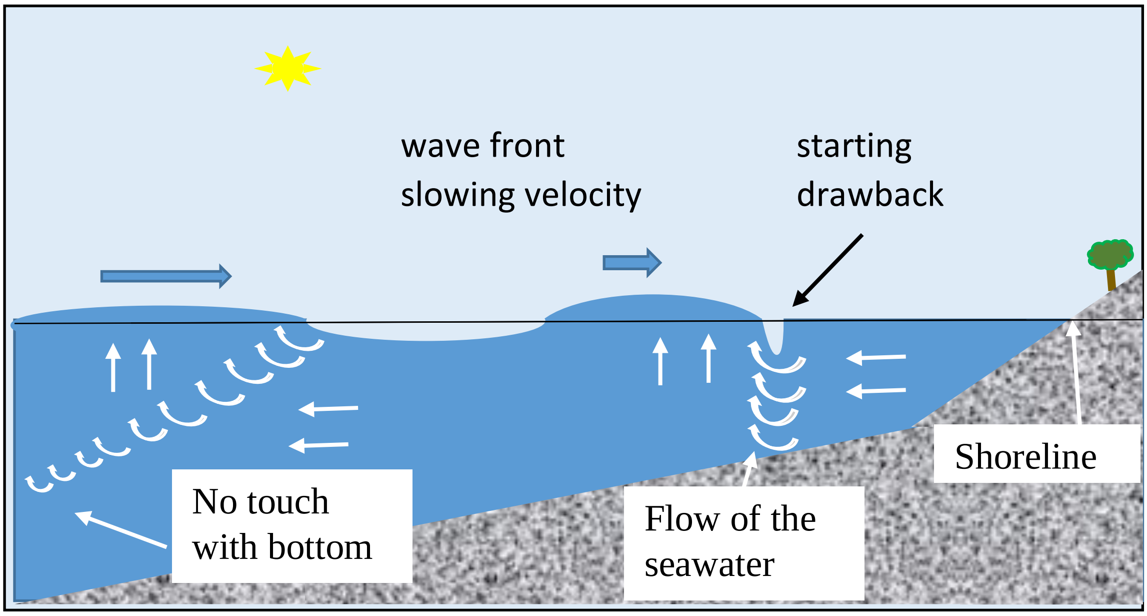

Fig. 9 Starting drawback of the tsunami wave

The drawback starts, when the velocity of the tsunami wave front is about 10 to 20 m/s depending on the energy of the tsunami wave. In the earlier situation the velocity of the tsunami wave front is so high, that the starting drawback is not possible and there is no touch with sea bottom (Fig. 9).

The single tsunami wave breaks on the deeper water and flows over the still seawater to the shoreline. The broken tsunami wave on the sea surface takes a big amount of seawater with during flowing to the shoreline and forms the many meters thick bore of the tsunami (Fig. 10).

Depending on the tsunami wave break over the still seawater the approaching bore could have depth of many meters [6]. The amount of the flowing seawater onshore is huge.

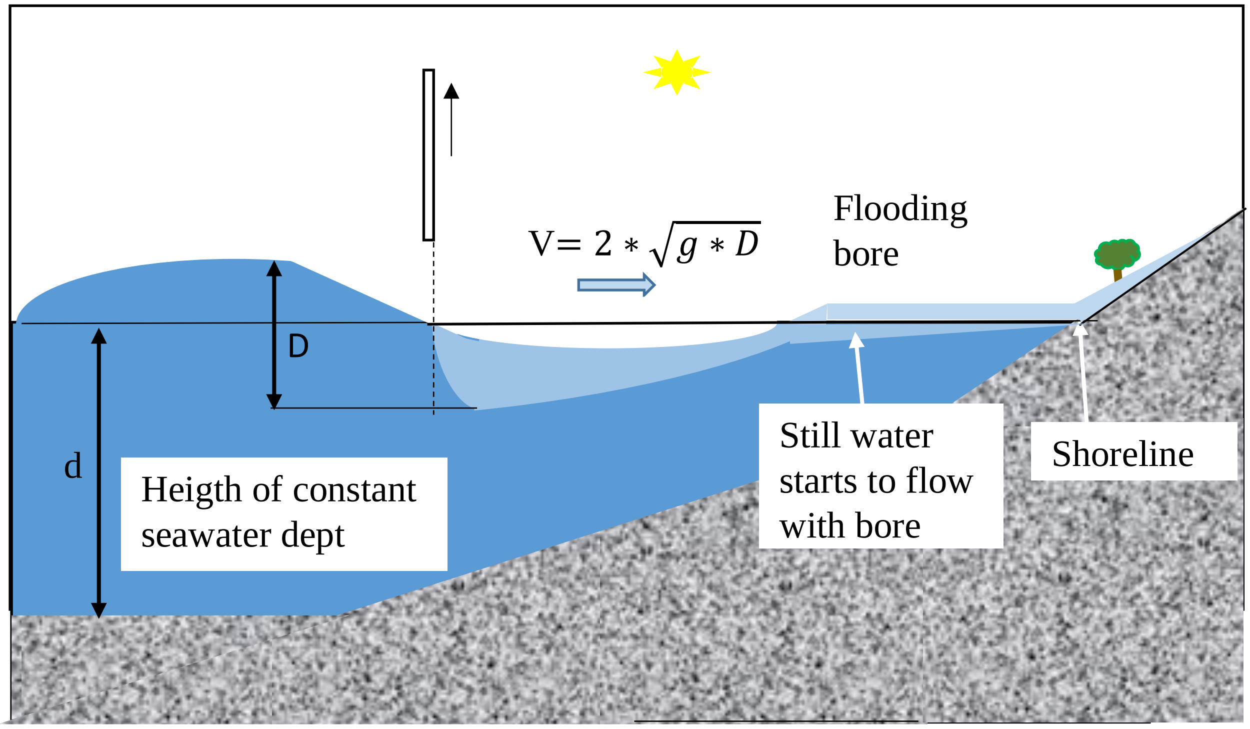

Fig. 10 Tsunami break wave flow over the still water

5. Tsunami shoaling to the deep and steep shore

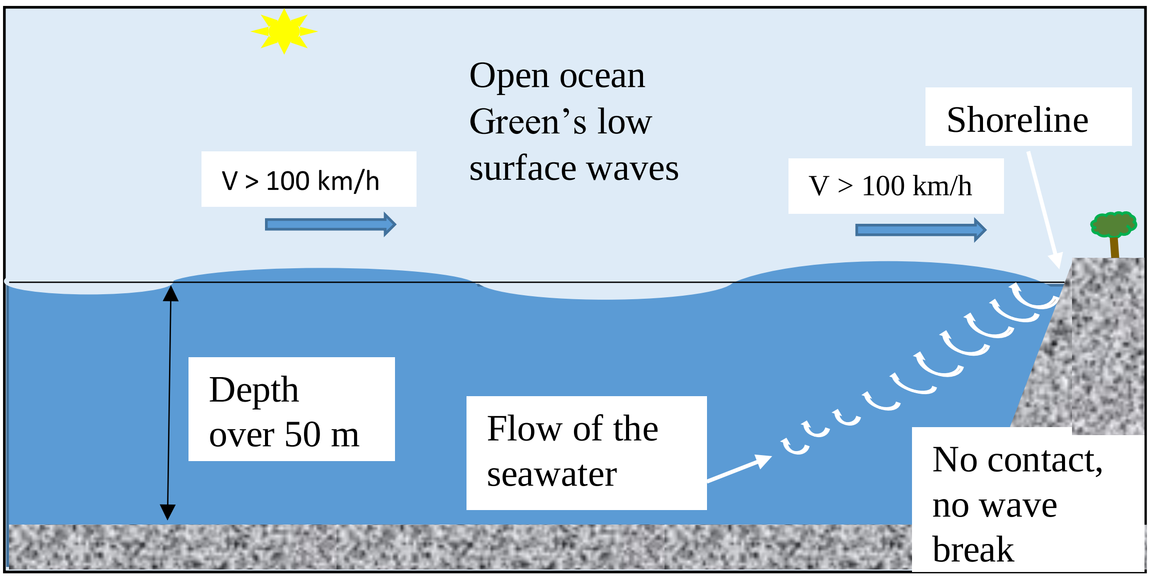

Fig. 11 Tsunami wave shoaling without wave break on deep and steep shore

Tsunami wave is minimal in the very deep and steep shore without the bore. The tsunami wave on the deep and steep shore will not brake and has no reinforcing effect from the seawater drawback. Green's waves come to shoreline and create alternately trough and crest and the amplitude of the tsunami wave is low.

This phenomenon is very general in the deep and steep shores as in Asia and in Japan [11]. According to this tsunami shoaling theory in the height of some meters above the maximum sea level there is onshore a tsunami safe place for the industry and the residential environment (Fig.11).

6. Tsunami bore flows upward along the river

The tsunami bore flows upward along the river, which is at the sea level (Fig12). Instead of the river it could be the canal or the fjord. When the first tsunami bore travels along the river mouth, it will take the water of the river with and the depth of the bore will increase depending on the energy of the tsunami.

The flooding bore in the river will slow down and stops. After that the very slow return flow begins, which is much slower than the return flow from the higher onshore areas.

When the second tsunami bore comes, it will flow over the first bore and the return flow and the formed huge water flow along the river causes many kilometers flooding.

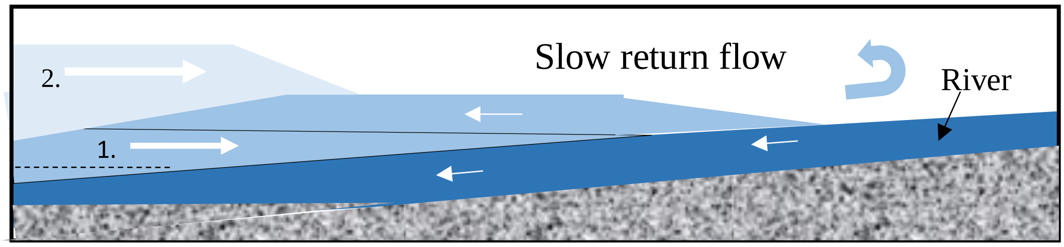

Fig. 12 First (1.) tsunami bore flows along river, begins to slow, stops and slow return flow begins. The second tsunami bore (2.) overflows causing enormous flooding along the river.

7. Tsunami wave damping nearshore

When the tsunami wave breaks nearshore, nearly the frictionless gravity tsunami waves change to the frictional horizontal flow by giving possibility to dampen tsunami. After the wave break tsunami will be dampened nearshore by utilizing the friction and mixing the seawater flows in the shallow seawater conditions. The water friction reduces the velocity of the tsunami bore according to the distance travelled. In addition the bore flow over still seawater reduces the velocity of the bore nearly to the half.

If in front of the coastline there is in the distance of about 10 km a shallow water, it is possible to build up the artificial coastline, which is parallel to the shoreline. It could be less than 10 m shallow seabed, a sandbank, a dike, a road or even an airport. These all will dampen the kinetic energy and flooding of the tsunami.

One natural damping example is the sandbanks in front of the city Faro in Portugal during the 1755 tsunami [12]. The kinetic energy did not broke the buildings of the city, however there was many hours flooding. City Faro survived.

8. Conclusions

The presented tsunami shoaling theory explains the facts:

- drawback and tsunami wave break
- calculation of velocity, depth and volume of the horizontal flow
- inundation depth and run-up height

- hydrostatic and hydrodynamic forces to buildings onshore
- duration of the tsunami flow
- minimal tsunami wave heights on the deep ocean
- tsunami shoaling on dry and wet seabed
- depth and velocity of the tsunami bore
- minimal tsunami waves on deep and steep shore
- tsunami flooding along river, canal and fjord

Above described phenomena support the presented tsunami shoaling theory. Many phenomena of the tsunami shoaling theory need more observations, measures, tests and verifications. This shoaling theory point out when and where have to make more observations and measures of the tsunami wave break.

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