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Madagascar: Understanding And Preventing the Tsunami

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Abstract – The Mayotte seismo-volcanic crisis in 2018 seems to have been resolved after the French government took preventive measures, in 2023, following studies, discoveries and scientific confirmations carried out on the situation.

Mayotte is then able to prepare for a possible tsunami risk.
The states bordering the somalian basin must also prepare, from effective way to this risk, by developing evacuation plans whose objectives are as follows :

- **Identify safe haven sites**
- **Secure coastal population in a minimum of time by guiding them to refuge sites.**
- **Broadcast in the media to support acculturation to tsunami risque**
- **Encourage authorities to organize evacuation simulation exercises. (IOC/UNESCO, 2013, 2023)**

Keywords – seismo-volcanic crisis, somalian basin, safe haven sites, acculturation to tsunami risque, evacuation simulation exercises

INTRODUCTION

In May 2018, hundreds of earthquakes occurred off the coast of Mayotte.
CNRS researchers took stock of the seismo-volcanic crisis that is frightening the population of Mayotte.
Since the beginning of this crisis, the BRGM (Bureau de Recherche Géologique et Minière), for its part, has been involved in its management and monitoring of the phenomenon.
In May 2019, an observation network : REVOSIMA and a MARION-DUFRESNE oceanographic campaign, as part of a campaign to observe seismic activity in Mayotte, contributed to the discovery of a new underwater volcano named Fani Maoré and a magmatic reserve at sea. Sea campaigns, REVOSIMA (2019) and SISMAORE (2020-2021) have made it possible to acquire new data to better characterize the nature of the oceanic crust in this area.
In addition to the usual movement of tectonic plates, this magmatic reserve and this marine volcano would have the effect of moving the island by several centimeters each month for several years (RICAHARD BOUHET/ AFP). **[1]**
In reality, behind Fani Maoré, the data reveal the presence of an immense volcanic corridor extending all along the Comoros archipelago, as far as Madagascar (MORGAN GILLARD, March 2023). More than 2,200 underwater volcanoes were then identified over an area 200 km wide and 600 km long.
"Although the source of deformation is deep and the condition for being a ***tsunamigenic*** source is not met, we

cannot exclude the sudden occurrence of a tsunami from a nearby source caused by submarine collapses of the roof of the magmatic reservoir or by submarine landslides originating on the very steep reef slopes of Mayotte, as evidenced by the numerous old tear scars visible on bathymetric maps" (Audru et al., 2006).

Thus, in 2023, the French government has put in place measures to prevent the risk of a tsunami that has become increasingly likely and that the conditions for producing a tsunami are increasingly considered to be met by the research carried out by scientists since 2019. **[2]**

In the event that a tsunami occurs in the Mayotte Sea, the countries of the same Somali basin, including Madagascar, in particular the North-West coasts, will not be an exception to the disasters.

This is why we wanted to work on the subject to write this scientific article. The objective of which is to appeal to authorities at all levels and the population itself to prepare for a possible risk of a tsunami.

The first thing we must do is to make the public understand that the tsunami is a natural disaster that the phenomenon can only be partly explained by science. The rest still relies on empiricism.

We will be able to estimate the propagation time of the tsunami and the prevention proposals that must be put in place immediately and in the coming years.

2.- METHODOLOGY

2.1.- Definition and characteristics of a tsunami 2.1.1.-

Definition

“SOO-NAH-MEE” : harbor wave (in Japanese)

The Japanese meaning of this word, “harbor wave”, perfectly sums up the common idea that we have of this fearsome phenomenon: the breaking on the coasts, completely unexpected, of a gigantic wall of water.

A tsunami refers to a series of ocean waves that can reach large amplitudes when approaching the coasts and have been caused by sudden disturbances in the ocean water layer. **[3]**

2.1.2.- Phases and characteristics

Generally speaking, a tsunami wave is generated by gravity efforts.

And when a source of sudden transverse disturbance occurs in the marine medie, this disturbance propagates by energy transfer. A tsunami can come from an earthquake with an intensity greater than seven on the Richter scale or landslides, volcanic eruptions or underwater explosions

Due to the inaccuracies and complexities of the origins of the tsunami, modeling from an equation of the triggering stage remains difficult.

A few minutes after the disturbance, the initial tsunami heads towards the depths of the ocean while another part heads towards the nearby coast.

The height of the first original tsunami is therefore divided into two halves.

The propagation stage is interpreted within the framework of the standard equations of fluid mechanics.

Given the influence of local particularities ("boundary conditions"), it is very doubtful that an exact mathematical description of the tsunami is possible.

Thus, up to approximations, the speed of propagation depends on the medium in which the wave propagates.

The breaking stage can be the subject of a project to prevent disaster risks depending on the morphology of the breaking coast.

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SCHOLAR AI Be Smart
Vol. 49 No. 1 February 2025, pp. 77-87

2.2.- Velocity potential

As a first approximation, we can assume that the sea is a perfect, incompressible and irrotational fluid during the propagation of the tsunami. **[4]**

The mass conservation equation for a fluid particle in the Navier-Stokes equations is given by the relation: $\frac{\partial \rho}{\partial t} + div\,(\rho \vec{v}) = 0$ Equation 1

ρ *density of the sea*; $\vec{v}$ *is the velocity vector*

For an incompressible fluid, , ρ is constant therefore : $div\,(\vec{v}) = 0$ Equation 2

One can then associate with $\vec{v}$, a scalar quantity φ that we will call **velocity potential** such that $\vec{v} = \overrightarrow{grad}\,\varphi$ That is to say that $\Delta\varphi = 0$. **[5]** Equation 3

The potential φ depends on x, y, z and t

2.3.- The propagation speed

Assuming the sea to be an incompressible, perfect and irrotaionnal fluid, the only restoring force that acts is the gravity and the equation of momentum in the gravity field is :

$$\vec{\nabla}\left(\frac{\partial \varphi}{\partial t}\rho + \rho\frac{v^2}{2} + p + \rho g z\right) = 0$$ Equation 4

Integration according to the spatial coordinates yelds the pressure p by the Bernoulli relation such that:

$$\frac{\partial \varphi}{\partial t} + \frac{\vec{v}^2}{2} + \frac{p}{\rho o} + gz = F(t)$$ Equation 5

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https://ijpsat.org/
Vol. 49 No. 1 February 2025, pp. 77-87

And which becomes the boundary condition for the potential velocity equation Neglecting nonlinear term and the integration constant F(t), one obtains:

$$\frac{\partial\varphi}{\partial t} + \frac{p}{\rho o} + gz = 0 \qquad \text{Equation 6}$$

On the water surface defined by $z = 0$, the pressure $p_{atm} = 1\ atm$ is the atmospheric pressure.

Thus we obtains on the sea surface

$$\frac{\partial\varphi}{\partial t} = -\,gz + \ Constante, \text{ for } z = 0 \qquad \text{Equation 7}$$

The normal component v_n of the wave particle is zero at the bottom of the ocean defined

by $-z = h$ and $\frac{\partial\varphi}{\partial z} = v_n = 0 for\ z = -h$ Equation 8

This equation 8 constitutes the boundary condition at the bottom of the ocean. [6]

Assuming again that $\frac{d}{dt} = \frac{\partial}{\partial t}$, the derivation with respect to t of the equation 7 yelds

$$\frac{\partial^2}{\partial t^2}\varphi = -g\,\frac{\partial z}{\partial t} = -gv_z = -g\,\frac{\partial\varphi}{\partial z} \qquad \text{Equation 9}$$

By setting $\varphi(x, y, z, t) = \psi\,(x, y).U(z).\exp(i\omega t)$ Equation 10

We have respectively

$\frac{\partial\varphi}{\partial t} = i\omega\,\psi(x, y).U(z)exp(i\omega t)$ and $\frac{\partial}{\partial t}(\frac{\partial\varphi}{\partial t}) = i^2\omega^2\,\psi(x, y).U(z)exp(i\omega t)$

$\frac{\partial\varphi}{\partial z} = \psi(x, y).(\frac{\partial}{\partial z}U(z))\,exp(i\omega t)$

We then obtain:

$$i^2\omega^2\,\psi(x, y).U(z)\exp(i\omega t) = -g\,\psi(x, y).(\frac{\partial}{\partial z}U(z))\exp(i\omega t)$$

That is to say : $\omega^2\,U(z) = g\,\frac{\partial U}{\partial z}$ Equation 11

The Laplace equation $\Delta\varphi = 0$ now reads : $\frac{1}{\psi}\left(\frac{\partial^2}{\partial x^2}\psi + \frac{\partial^2}{\partial y^2}\,\psi\right) + \frac{1}{U}\frac{\partial^2}{\partial z^2}U = 0$ Equation 12

Designating by k the separation constant, we obtain from Equation 12 these two equations :

$$\frac{\partial^2}{\partial x^2}\psi + \frac{\partial^2}{\partial y^2}\,\psi + \,k^2\psi = 0 \qquad \text{Equation 13}$$

$$and\ \ \frac{\partial^2}{\partial z^2}U - \,k^2U = 0 \qquad \text{Equation 14}$$

International Journal of Progressive Sciences and Technologies (IJPSAT)
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https://ijpsat.org/
Vol. 49 No. 1 February 2025, pp. 77-87

Equations for which the solutions are respectively:

$\psi(x,y) = A\, exp\, i(k_x x + \; k_y y)$ Equation 15

$$where\ k^2 = \; k_x^2 + \; k_y^2\ and\ k\ the\ waves\ water$$

And $U(z) = cosh\, k(z + C)$ C *is an integration constant* Equation 16

The boundary condition for $z = -h$ gives $U_z(-h) = k\, sinh\, k(-h + C) = 0$

The constant $C = h$ and designes now the ocean depth.

From equation 11, one obtains $\omega^2 = gk\, tanh\, k(z + h)$

Thus, on the surface of the sea, where *z = 0,* the dispersion relation becomes

$\omega(k) = \sqrt{gk\tanh(kh)}$ or $\omega(k) = \sqrt{g\,\frac{2\pi}{\lambda}\tanh\,(2\pi\,\frac{h}{\lambda})}$ Equation 17

$$\lambda\ is\ the\ wavelenght$$

For phase propagation speed, we have $c^2 = \frac{\omega^2}{k^2} = \frac{\lambda g}{2\pi} tanh(2\pi\frac{h}{\lambda})$ Equation 18

For $h \ll \; \lambda, we\ can\ get\ c = \; \sqrt{gh}$ Equation 19

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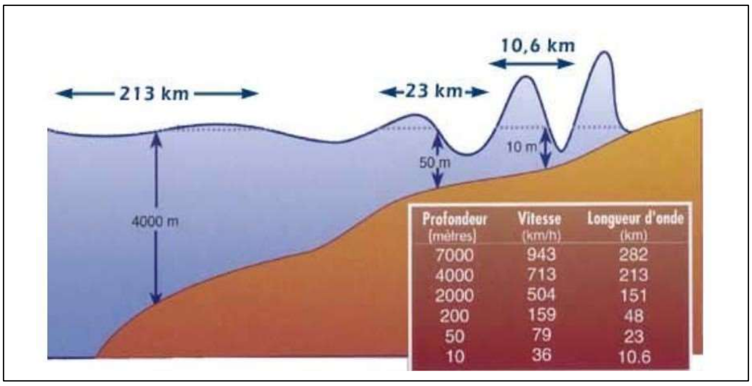
https://ijpsat.org/
Vol. 49 No. 1 February 2025, pp. 77-87

This result is similar to the figure published by an international tsunami working group such as: the International



Tsunami Center, NOAA, the National Weather Service, the CEA geophysical laboratory, the Intergovernmental Oceanographic Commission (UNESCO/IOC)**[3]**

Figure 1 Speed propagation of tsunami, wavelenght, depth

2.4.- Tsunami risk in Madagascar

The tsunami risk in Madagascar has been found to be moderate but since the seismo- volcanic crisis in Mayotte since 2018 in connection with the formation of the underwater volcanic chain ***Fani Maoré*** which led to an increase in the risk of tsunami in Mayotte.

A tsunami in Mayotte will affect all the Somali and Comoros basins, including Madagascar, in particular the northern and northwestern parts.

Based on the bathymetric maps and assuming a source point of disturbance in the Mayotte area, we propose to make an approximate calculation of the propagation time of a tsunami to reach Madagascar.

3.- RESULTS AND DISCUSSION

Several potential sources of tsunami threaten the Somali Basin:

- Seismic activities in the Mayotte Sea
- Underwater collapses of the magma reservoir roof
- Submarine landslides originating on the very steep reef slope of Mayotte
- Presence of a subsidence zone caused by deep fluid circulation.
- The Karthala volcano of Grande Comores
- The subduction zones of Markan in Pakistan and Sumatra in Indonesia.**[2]**

The geological context of the region indicates that small earthquakes can be precursors of a major earthquake. In addition to the formation of the submarine volcano and the presence of the East African rift, global warming is added and all this is not at all a good sign because all these situations can increase the probability of a major earthquake at sea and consequently a devastating tsunami.
A tsunami in the Mayotte Sea is among the five potential natural disaster risks that could affect Mayotte, Madagascar and the Comoros Islands in the future (JAMI, Epicurieux, 2022).

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https://ijpsat.org/
Vol. 49 No. 1 February 2025, pp. 77-87

METHOD 1 :

For a global calculation, between Mayotte and Madagascar, the depth of the ocean given by the bathymetric map is around 3000m.

Using Equation 19 and the figure 1, the wavelength is 230 km and c = 600km/h.

METHOD 2 :

We can then propose a simulation of the propagation of a probable tsunami. We'll use a bathymetric of NW of Madagascar given in figure 2

Assuming that the source of the tsunami is in the area where Fani Maoré is located, for an estimated distance of 250 km, the wave propagation time is then of the order of 25 minutes to reach the nearest northwest coast of Madagascar.

Let's do a more detailed calculation of the simulation:

Let's start by considering four paths P_1, P_2, P_3, P_4 of the wave from the source to the coast of Madagascar.

Each path P_i is divided into five portions $P_{i1}, P_{i2}, P_{i3}, P_{14}, P_{i5}$ $(i = 1, 4)$

For each portion characterized by an area of the same depth, the propagation speed is $c = \sqrt{gh}$

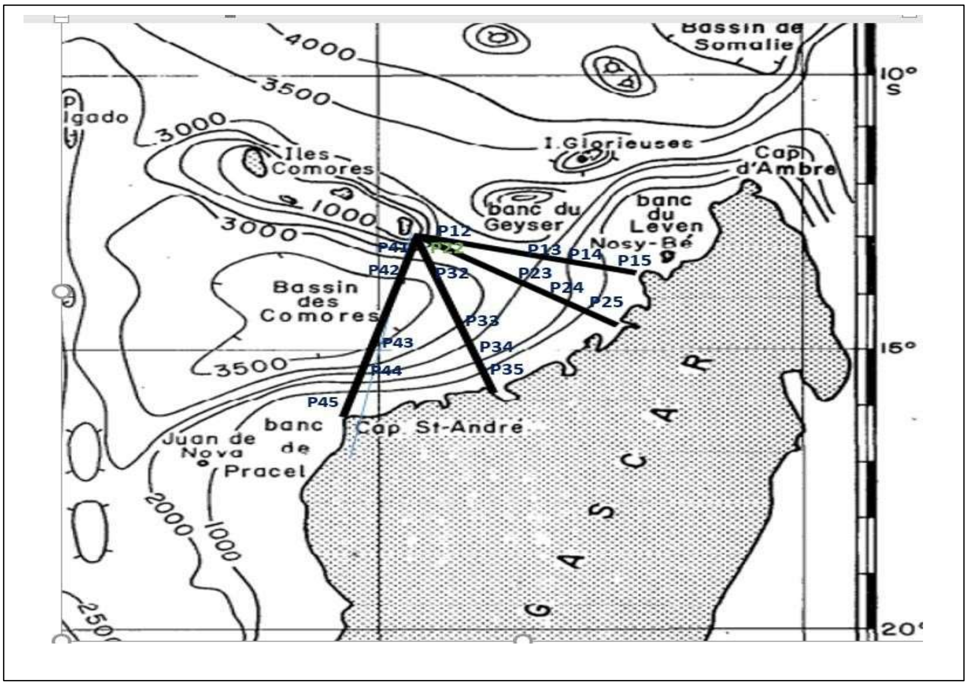

Figure 2 : Bathymetric map of NW of Madagascar
Source : ORSTOM, 1991, Etude Bathymétrique du NW de Madagascar

The propagation time on each portion is $t = \dfrac{lenght\ of\ portion}{propagation\ speed}$

The propagation time on a path is therefore the sum of the durations t_i

The time of propagation from the source to coast of Madagascar is estimated 35 minutes.

The figue 3 gives an idea at a simulation of arriving of waves of tsunami in case of the souce is situated nearby Mayotte.

One gets the value table

Portion P_{ij}	Longueur de la portion (km)	Profondeur de la portion (m)	Vitesse (km/h)	Durée de trajet (mn)	Durée totale (mn)
P11	30	1000	300	7	
P12	125	3000	600	13	
P13	40	2500	550	3,5	
P14	30	2000	500	4	
P15	30	1000	300	7	
$\boldsymbol{P_1}$	**255**				**34,5**
P21	30	1000	300	7	
P22	120	3000	600	13	
P23	55	2500	550	7	
P24	35	2000	500	5	
P25	10	1000	300	2,5	
$\boldsymbol{P_2}$	**250**				**34,5**
P31	30	1000	300	7	
P32	30	3000	600	3	
P33	120	2500	3500	11	
P34	30	2500	550	3,5	
P35	40	1000	300	8	
$\boldsymbol{P_3}$	**250**				**32,5**
P41	30	2000	500	4	
P42	30	2500	550	4	
P43	160	3200	600	16	
P44	40	2500	550	7	
P45	30	2000	500	3.5	
$\boldsymbol{P_4}$	**250**				**34,5**

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https://ijpsat.org/
Vol. 49 No. 1 February 2025, pp. 77-87

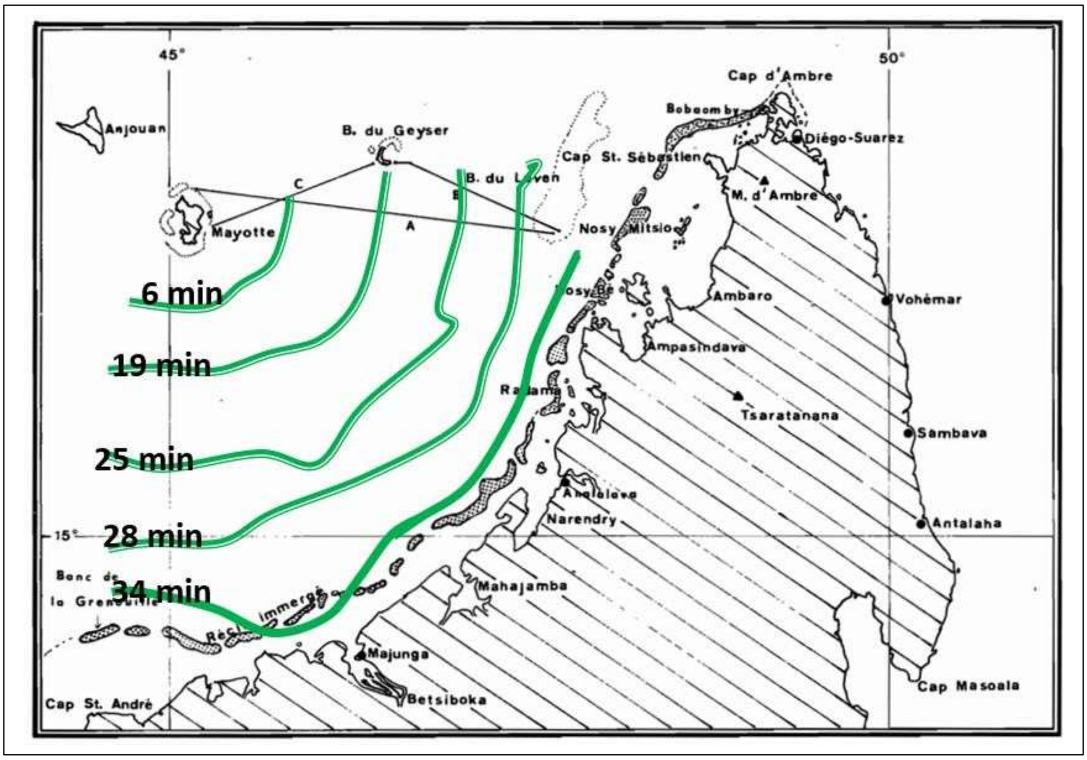

Figure 3: Simulation

4.- CONCLUSION

Despite the very moderate tsunami risk (10%), Madagascar is threatened by tsunamis from distant sources (case of the Sumatra tsunami) and tsunamis from nearby sources (case of possible tsunamis due to the new volcanoes recently discovered in Mayotte). **[1]**

If in Sumatra, the people had only a few minutes to flee, the tidal wave took two hours to reach India, where 16,000 people died. "These people should never have died," says PARAMESH BANERGEE, geophysicist at Nanyang Technological University in Singapore.
Technically, it would have been quite easy to install a tsunami warning system for the Indian Ocean."

There are now 53 detection buoys in service in all oceans, including 6 in the Indian Ocean (out of the 27 planned). **[7]**

Moreover, for distant tsunamis, we have seen that Madagascar is protected by the Mascarene Plateau. Energy losses are significant that the Maldives and Reunion Island have only seen sea level rises.

For nearby tsunamis, thirty minutes would not be enough to prepare unless preventive measures had already been taken in advance, measures called early.

Faced with a tsunami, the dramatic Indonesian (2004) and Japanese (2011) experiences have shown that the only effective way to increase the chances of survival was the preventive,

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Vol. 49 No. 1 February 2025, pp. 77-87

massive and rapid evacuation of coastal populations. The places where human losses were observed to be high were the places where adapted behaviors were lacking.

The tsunami is a natural disaster that has had the reputation of thwarting the predictions of scientific calculations. We must therefore prepare the exposed populations to face this risk of disaster.

At the international level, the Intergovernmental Oceanographic Commission (IOC) of UNESCO has established a Tsunami Programme in which the Coordination Unit assists IOC member states in assessing tsunami risk and implementing tsunami early warning (TEW) systems.

Under the aegis of IOC/UNESCO, regional tsunami monitoring and information centres (Tsunami Service Providers, TSPs) are now operational worldwide and are able to disseminate an alert to national authorities.

At the national level, coastal states of an entire ocean basin are encouraged to take appropriate safeguards and prepare their populations. (IOC/UNESCO, 2008 and 2013).

The objectives of evacuation plans are:**[8]**

- Identify and list refuge sites (high altitude locations and places where people could take refuge).

- Secure coastal populations in a minimum of time by guiding them to these refuge sites.

- Disseminate in order to support acculturation to tsunami risk.

- Encourage authorities to organize evacuation simulation exercises (IOC/UNESCO, 2013 and 2023)

As this work has already been started by the Malagasy BNGRC, the GFDRR (Global Facility for Disaster Reduction and Recovery) in the context of earthquakes, floods and tropical cyclones, we can make another effort to extend these measures for tsunami hazards.

Since 2018, warning systems have been improved following the discovery of gravitational waves, which makes it possible to better anticipate the arrival of the tsunami.

There is even currently software developed from this discovery to better alert populations on vulnerable shores, such as the LastQuick application.

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