

ASSESSMENT OF STRUCTURES SUBJECTED TO TSUNAMI LOADINGS

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ABSTRACT: This paper focuses on the key criteria and methodologies required to undertake a structural assessment of loads generated by Tsunamis. With focus on the Indian Ocean Region methodologies identified and explored, focus on inundation depth through hazard mapping, site-specific loads, probable return periods, performance levels, load paths, and load combinations. These methodologies which are utilised to varying extents in both Japan and the Pacific states of the USA are placed in the context of the Indian Ocean Region and evaluated against the current socio-economic challenges, in particular poverty and population growth. From an analysis of methodologies and corresponding pro-active strategies it is evident that structure related techniques have potential to play a major role in mitigating risks. However, until a sound structural assessment is developed current knowledge on strengthening structures should be part of a holistic approach that utilizes several mitigation techniques such as warning systems, education awareness and evacuation plans.

1. INTRODUCTION

This paper utilises structural engineering knowledge to inform coastal regions surrounding the Indian Ocean of remedial actions that can be adopted to strengthen structures and in turn mitigate the risks (loss of life, livelihood and damage to assets) that result from a tsunami.

Mitigating risk through building design focuses on developing programs to retrofit or rebuild structures that are vulnerable to failure/collapse, given an expected return period and expected inundation depth. In developing programs, methodologies must be firstly established to evaluate the structural adequacy of already existing structures.

The following paper is divided in to three main sections which assess the viability for the implementation of methodologies and programs to mitigate risks associated with Tsunamis. Section one (1) introduces the concept of risk and vulnerability and the means by which risk can be mitigated through strengthening structures; section two (2) highlights the key criterion and in turn a holistic methodology for undertaking a structural assessment of tsunami loads; and section three (3) reviews the social and engineering challenges, and the viability of implementing pro-active strategies to reduce structural damage resulting from Tsunamis in the Indian Ocean region.

In interpreting this paper it is important to understand that strengthening a structure is not a panacea for disaster prevention. Rather it is a means by which the risks associated with natural hazards can be mitigated. In many regions socio-economic conditions may constrain the implementation of engineering-based designs to strengthen structures; hence consideration of alternative actions such as site-planning and management, early warning systems, and community based education programs should be considered.

Furthermore, at the time of writing, policies that relocate communities away from the coastline have been the preferred solution for mitigating risk [1]. Although sound in theory, such policies come at high social, cultural and economic costs. This paper, hence looks at the potential for engineering based strategies to be implemented at a community based level to contribute to a more effective solution of mitigating risks associated with natural hazards.

2. RISK ASSESSMENT

With the ever-swelling urban populations of coastal regions surrounding the Indian Ocean ‘hazard mitigation measures’ are required to be used as working tools to decrease risks (loss of life, damage to livelihoods) associated with natural disasters [2]. The United Nations has developed equations for risk which incorporating factors such as strength of the hazard, population and physical exposure [3]. However, due to the focus of this report being strengthening structures subjected to Tsunamis, the equation for risk (Eq. 1) has been simplified to be determined by potential run-up water height and vulnerability [4].

$$\text{Risk}(R) = \text{Runup}(H) \times \text{Vulnerability}(V) \quad (1)$$

Risk throughout this report, rather than referring directly to loss of lives as per the UNDP’s Disaster Reduction Report [4], refers to the probability of structural failure from a Tsunami. Structural failure is considered the violation of a defined limit state whether it is collapse of all or part of the structure.

Decreasing run-up height can be achieved by use of sea walls, levees and plantations and/or alternatively relocating structures in regions of elevation higher than the inundation depth [5]. Based on structural assessment the considered option for risk reduction in regard to strengthening structures, focuses not on decreasing run-up height but rather decreasing vulnerability [3]. Vulnerability is the characteristics of a person or group and their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard. Achieving a reduction in vulnerability advocates that damage to livelihood/assets can be decreased through undertaking engineered design consideration, ensuring that structures are properly constructed and, that structures have continuous load paths.

However, it must be realized that mitigation of risk by reducing vulnerability through strengthening structures only has the ability to survive an anticipated load case, and will not ensure that a structure will withstand an unknown intense condition associated with a larger event.

3. STRUCTURAL ASSESSMENT

In order to develop methodologies and implement remedial actions for the strengthening of structures in coastal areas surrounding the Indian Ocean, a qualitative and quantitative analysis of the expected magnitude of potential loads must be evaluated. In analyzing the expected magnitude and effects of a Tsunami on a structure the following methodology will be considered:

- Identification of inundation depth as a key variable and the need for hazard maps to be developed to clearly classify key regions at risk;
- Exploration of site-specific loads that should be considered to quantitatively determine whether a structure will fail;
- Investigation of the probabilities of a risk occurring (return interval);
- Understanding of the varying degree of safety that can be applied to a structure; and
- Determining how the above stated can be combined to develop satisfactory structural design and reduce structural vulnerability to disaster loadings.

3.1 Inundation Depth and Hazard Mapping

Inundation is the design-use tsunami depth (metres) of the flood conjured at the site [6]. It differs from run-up as run-up is the elevation in metres reached by measured sea-water relative to some stated datum such as mean sea level, mean low water, or sea level at the time of the tsunami measured ideally to a point that is the local maximum at the horizontal inundation. Due to an unavailability in numerical models to quantify velocity with particular past Tsunami events, velocity throughout this report is assumed to be related to and a function of inundation depth (Eq.2).

$$u = \frac{1}{2} gh^{1/2} \quad (2)$$

Numerical modeling and research following past catastrophic tsunami/flood events have enabled regions such as Japan and various Pacific Nations to develop hazard maps. A hazard map indicates the estimated inundation depth given a disaster return interval [6]. Unlike Pacific Nations and Japan, there are no existing regional hazard maps for areas surrounding the Indian Ocean, except for storm surges in the Indian subcontinent, which not only creates uncertainty in allocating a limit-state to a given structure but also in calculating site specific loads. At the time of writing current proposals were being formulated for the development of hazard maps in some locations surrounding the Indian Ocean Region [7]. However in places such as Banda Aceh, available topographic maps are only available at 25-metre contours [7]. Given a contour zoning of 25-metres, velocities have the capacity to increase from approximately 1.5m/s at an inundation depth of 1-metre to 7.8m/s at an inundation depth of 25-metres. From 1-metre to 25-metre inundation depth lateral hydrostatic pressures may lie anywhere between approximately 200kN/m² and 5700kN/m² (section 3.2). This variability in loading on a structure creates a key problem in estimating the resistive loading of a structure and hence would require the conservative assumption that all structures within a 25-metre rise would need to be equally strengthened due to ambiguity in expected inundation depths.

3.2 Site-Specific Loads

Site-specific loads considered when determining whether a structure can withstand the velocities generated by a tsunami include lateral and vertical hydrostatic loads; localised scour; debris impact load; and hydrodynamic loads.

All of these Tsunami generated loads explored are a function of inundation depth. As a result of reliance on the accuracy in inundation depth, something that is yet to be established, care should be taken in applying the site-specific loads to design. Results obtained given a certain inundation depth should be approached with caution and utilized only as an approximate value.

Hydrostatic loads are caused by an imbalance of pressure due to differential water depth of opposite sides of a structure or structural members [8]. Hydrostatic loads considered include loading in the horizontal and vertical direction otherwise respectively known as lateral and buoyancy.

Lateral hydrostatic loading (kN/m²) is the pressure in the horizontal direction that acts on the pressure-exposed surface of buildings (Eq. 3) [6]. With the exception of surge force, lateral hydrostatic loading can be considered the most critical load in terms of magnitude. However, in applying this equation, it should be recognized that the formula is designed for flat land with no obstacles which as a result produces larger wave pressures. In addition, the formulae can be considered limited, because (1) the wave acts in the horizontal direction acting on the pressure exposed surface, (2) it is determined as a function of inundation depth and hence inundation depth must be known, (3) window openings and other small apertures are not thought to have any great effect on tsunami loads they are not included.

$$F_{H1} = pg(3h - z) \quad (3)$$

This formula can also be presented as a force (kN) in the horizontal direction that acts on the building (Eq. 4) [6].

$$F_{H2} = \frac{1}{2} pg \left(h + \frac{Up}{2g} \right)^2 \quad (4)$$

When designing for either the lateral pressure (kN/m²) and or force (kN) consideration should be given to the vector sum of all forces on the wall due to the structure being subjected to a backwash velocity.

Buoyancy is a vertical hydrostatic force (Eq.5). Underground structures can be affected by buoyancy when the surrounding soil becomes saturated. Major effects expected from buoyancy include undermining of footings and failure in load paths between floor slabs and walls.

$$F_B = pgV \quad (5)$$

Scouring is the process by which fill materials are removed as a result of floodwaters or tsunami induced waves. Scouring, rather than being a function of the average current velocity, water depth, and foundation dimensions, is

considered a time dependent accelerating phenomenon which is dependent on soil type and can be determined as a function of percentage of Stillwater depth [9] Currently the only accessible method for measuring scour is as a percentage of inundation depth dependent on a soil type (Table 1) [9]. Although in some cases the results obtained from these percentages appear reasonable, consideration should more specifically be given to the velocity at which a particle becomes dislodged and the presence of possible vortex's that commonly occur around the base of foundations.

Table 1 Localised Scour (Tsunami Condition)

Soil Type	Expected Depth (% of inundation)
Loose Sand	80%
Dense Sand	50%
Soft Silt	50%
Stiff Silt	25%
Soft Clay	25%
Stiff Clay	10%

Given the expected scouring conditions in Table 1, if the design Stillwater depth is equal to an inundation depth of approximately 2-metres in coastal regions, scouring under the worst soil conditions has the capacity to range from 1 to 1.5-metres. This appears to be reasonable against the formation of current guidelines such as those published by Tamil Nadu who stipulate that all foundations should be greater than 1-metre [10].

Debris Impact loads (kN) are loads imposed on a building resulting from objects carried by moving water (Eq. 6). The magnitude of these loads is influenced by the structure's position in the potential debris stream.

$$F_i = \frac{wv}{gt} \quad (6)$$

Under situations in which debris include portions of damaged buildings, utility poles, portions of previously embedded piles and/or empty storage tanks, a weight of 453.59kg be used [9]. For structural material of wood construction $t = 1$ -second, for structural material of reinforced concrete $t = 0.1$ -second, and for structural material of steel construction $t = 0.5$ -second [9].

Hydrodynamic loads are a result of water flowing around a structure and if greater than 3.05m/sec are a function of structure geometry and include frontal impact on the upstream face, drag along the sides, and suction on the downstream side [9].

Surge force (kN) similarly to lateral hydrostatic pressure is total force per unit width on a vertical wall subjected to a surge from a leading edge of a tsunami which approaches the structure as a bore or bore-like wave (Eq. 7). Such force is only induced on a structure for a fraction of a second and is likely only to occur on the first wave or breaking waves. Due to the excessive magnitude of surge force (approximately four times lateral hydrostatic force) consideration needs to be given on the expected spatial locations of the force. Such analysis is required as strengthening all structures against surge force would be both an expensive and impractical exercise.

$$F_s = 4.5pgh^2 \quad (7)$$

Drag force is a quadratic function of inundation depth and calculated by multiplying flow velocity squared times the inundation depth (Eq. 8) [6]. Drag force, although quantitatively much smaller than lateral hydrostatic loads and surge forces must be considered in-particularly in designing for perpendicular walls. The drag coefficient can be viewed as either non-dimensional (1.0 for circular piles, 2.0 for square piles, 1.5 for wall sections) or as a ratio of the breadth to width of the structure [9].

$$F_D = \frac{pC_dAu^2}{2} \quad (8)$$

Eliminating anomalies such as wave direction and spatial location, quantitative formulation highlights that the forces from surge and lateral hydrostatic are the most critical on a structure. It should be noted that the critical load induced on a structure will vary given its spatial location. While structures located on the shoreline of the

low lying coastal region may be most vulnerable to direct local hydrostatic pressure and surge forces, settlements in adjacent areas may be more vulnerable to scour and drag forces.

Despite the ability to perform a quantitative loading analysis for a known inundation depth designing structures, from a cost-effectiveness perspective, which in many cases is the underlying challenge, should consider firstly the limit-state under which the event is expected to occur and secondly the performance levels expected from the structure.

3.3 Limit-State Design

Loads subjected on structures due to a natural phenomenon have randomness in both time and space. This randomness of time is considered in the terms of a 'return period', which is the average (or expected) time between two successive statically independent events [11]. However in regions such as the Indian Ocean, numerical solutions from data records, yearly and daily maxima for a given return period of a natural disaster are not always available due to insufficient data and a lack of understanding of the means by which to predict future loading [11].

The design criteria governing the satisfactory behavior or reliability of a structure of above elements relate to one or more levels of loading which in some codes are referred to as limit-state design. In consideration of the reoccurrence of Tsunamis in the Indian Ocean Region the following limit-states are currently being considered as part of the Guidelines for disaster reduction on the coasts of the Indian Ocean:

- Serviceability Limit-State Design is for an extreme event with a return period of 50-years or less which results in no deaths, no injuries and structures are undamaged and functioning properly;
- Ultimate Limit-State Design is for an extreme event with a return period of 500-years which results in no deaths, minimal injuries and structures may be damaged but still standing;
- Disaster Limit-State Design for an extreme event with a return period of greater than 5000-years which results in minimal deaths, minimal injuries, and minimal loss of structures and infrastructure.

Currently information regarding the size of historical Tsunamis are in-conclusive and hence create uncertainty in expected return-intervals. Based on the above stated limit-states one would assume that the return period for an event similar to the 2004 Indian Ocean Tsunami would be categorised as being at the disaster limit state. However based on the frequency of tsunamis over the last 170 years geotechnical advice has suggested that best estimate of reoccurrence of a 10-metre tsunami (2004 Indian Ocean Tsunami), is of the order of a 100-years and it is not a rare one off event [12]. Based on the ambiguity in the return-Intervals of events what performance level should we require under varying limit-state designs?

Furthermore, limit states must be used with caution and applied independently for varying multi-hazard and natural disasters. For example, the frequency and damage resulting from cyclones in the Indian Ocean Region differ from Tsunamis. Tropical storms greater than 17m/s range from an annual average of 5.4 in the North Indian Basin to 10.4 in the South Indian Ocean, and severe tropical cyclones greater than 33m/s from an average of 2.5 to 4.4m/s [13]. Hence from these results it is evident that the return period of a severe cyclone is less than 50-years. As a result of the variance of frequency, the objectives in regards to mitigating risks will vary dependent on the risk type.

3.4 Performance Levels (Factors of Safety)

The level of damage tolerated by an owner or community depends on an integrated set of decisions based on the importance of a building, understanding the consequences of damage, and deciding how much damage can be tolerated [14].

In the event that a given loading and limit state design are known, what factors of safety should be applied to ensure that a building's structural design is fully or partially functional? The level at which a building is to be strengthened is governed by performance levels. A performance level is the amount of damage the owner can tolerate and the ability of the building to support its intended use after the tsunami.

In establishing a performance level, local communities under the assistance of engineers should consider the return interval of the hazard, the desired level of reliability and the vulnerability of the structure. Table 2

highlights some qualitative aspects that correspond to a minimum safety, re-occupancy and/or operational performance level [14].

Table 2 Performance Level Criterion

Performance Level	Description
Minimum	<ul style="list-style-type: none"> • Buildings located, designed and constructed to a level that can resist hydrostatic and hydrodynamic loads without being moved from their foundations. • Buildings might suffer extensive damage from flooding and may not resist the impact of debris, wave break force, scour or ground failure. • Occupants of these buildings must be prepared to evacuate site to be safe
Safety	<ul style="list-style-type: none"> • Structural integrity is maintained. • Buildings located, designed, and constructed to this level should withstand hydrostatic, hydrodynamic, debris and wave-impact forces. • Foundations should be satisfactorily designed in anticipation of scour erosion and saturation.
Re-occupancy	<ul style="list-style-type: none"> • Buildings located, designed and constructed to this level can withstand the same forces as safety level buildings and be occupied within a few weeks following clean up, minor repairs, and restoration of utilities. • Meeting this standard would require more stringent location restrictions and choice of flood-resistant materials. • Building locations and the elevation of the lower floor are critical considerations.
Operational	<ul style="list-style-type: none"> • Buildings located, designed and constructed to this level can withstand the same forces as in the re-occupancy level, but should have back-up emergency systems (utilities) to support the use of the building immediately after the tsunami. • These building would preferably be placed outside the tsunami hazard zone.

In the case of a multi-refuge design, a performance level of operational should be required. A multi-refuge applies to buildings and services such as fire stations, power substations, hospitals, sewage treatment facilities. These facilities generally should not be located in inundation zones and relocation of these types of facilities out of inundation areas should be an integral part of the tsunami mitigation plan.

3.5 Design Load Combinations

When analysing load force, limit-state and performance levels, the generated load combinations need to be checked against the resistive force of all structural elements (foundations, footings, columns, roof tie-ins, walls and floors) both independently and in combination to determine whether strengthening of one or all components is required.

All considered loads applied to a structure and on structural components should be considered both alone and in combination. This should be done in such a manner that the combined effect will result in the maximum loads and stresses that can be withstood by the structure [16]. In addition designers should utilize the most unfavorable effects of either seismic loads or combined wind and flood load [16].

Under most circumstances building codes and engineering standards are the best available guidance for identifying basic load combinations. Such programs have been implemented in Pacific nations through the adoption of strength design combinations [15]. However, applying load combinations to structures in the Indian Ocean are not as simplistic as adopting already stipulated Pacific Nation load combinations. In applying the load combinations for Tsunami events in the Indian Ocean Region the ability to apply such load combinations should be reviewed. For example if the lateral hydrostatic pressure as explored in section 3.2, which is an upper bound limit of the actual expected load, is it realistic for economic purposes to multiple the load by a safety factor.

3.6 Load Paths

Although not quantitatively evaluated as part of this paper, when strengthening structures, special consideration should be taken in ensuring a definite load path. A deficiency in the connections can lead to structural damage or collapse. A continuous load path should effectively link through connections (nails, screws, bolts, and welds) and forces acting on the exterior, starting with the non-load bearing walls, roof covering and decks and windows and doors. A continuous load path should ensure that the following connection types are satisfactory:

- Lateral Load is applied to the flat roof;
- Load is transferred from the lateral wall to the horizontal diaphragm;
- Load is transferred from the diaphragm to the shear wall (only full high sheathing segments are assumed to provide resistance to lateral loads); and
- Load is transferred from the shear wall to the foundations.

The necessity to ensure continuous load paths is evident when identifying failure mechanisms as a result of the 2004 Tsunami. Construction failure was most evident at the beginning of the load path in-particularly at the effective link, i.e. failure from lateral loads on roofing elements and diaphragm walls from shear walls, and or footings and foundations from floor slabs and walls from scouring loads.

3.7 Visual Inspections

From an evaluation of loading, the methodology adopted for assessing structures should holistically incorporate site-specific loads, performance levels, limit-state design and load paths.

In addition, visual inspection and the use of images to presents structural defects play a major role in advising and teaching communities of possible structural failure modes. Through identifying failure mechanisms in foundations, footings, floors, columns, wall, roofs and roof ties of already existing structures, corresponding remedial measures can be adopted to strengthen areas in which defects exist. Although this does not aim at increasing the structural capacity of a structure for an estimated load, such assessment and remedial action will undoubtedly increase resistive forces, which in a time when assessment criteria are still being reviewed is more effective than 'doing nothing'. An example of such an assessment was undertaken by the Australian Engineering Relief Team in the Maldives [17]. Based on the visual inspections of over 24-schools following the Indian Ocean Tsunami, a spreadsheet outlining the damage type, and remedial actions required of each school were determined.

4. CHALLENGES

In considering the implementation of site-specific load combinations to improve the robustness and stability of structures, a number of key engineering and social challenges need to be addressed in order to advance the process of rebuilding and retrofitting multi-hazard disaster prone regions. These include the following:

4.1 Engineering Challenges

- The intensity and frequency of multi-hazard disasters along with topography of the land vary greatly along the coastland of the Indian Ocean which in turn alters the site-specific loads and the expected structural damage.
- Currently, quantitative data including maximum inundation depth and loads in combinations are not available to develop numerical models for determining the structural reliability of already existing structures.
- The magnitude of Tsunami site-specific loads makes it inappropriate for designs to be resisted using traditional elastic regimes. Elastic regimes are governed by serviceability limit state and deflection rather than strength. When considering the possible aftermath of an extreme event it is stability that is critical and hence theories outside the elastic theory need to be considered [11].
- With inundation depth acting as the current key variable, hazard mapping is essential in developing quantitative analysis to strengthen structures.

4.2 Social/Economic Challenges

- Dealing with the vulnerability of existing buildings is difficult due to limited numbers of alternatives and the cost associated with remedial structural actions which have the capacity to withstand site-specific loads.
- Housing varies within the Indian Ocean Region due to cultural differences and inequity in wealth distribution. Hence, reconstruction and retrofitting strategies face the dilemma of devising a scheme that provides equal assistance for all communities and/or subsidies and grants for those who want to rebuild or retrofit their own homes.
- If a large number of households start rebuilding and/or retrofitting at once there is potential for shortages of materials and building specialists. Proposal and procurement planning must be undertaken prior to major construction phases to ensure that adequate supplies and building materials (especially legally felled timber) at appropriate prices are available.
- When implementing building guidelines basic design standards must be adopted to achieve construction quality and must be controlled and supervised.

5. PROPOSALS

Based on the methodologies for undertaking a structural assessment, it is evident that an essential part of strengthening structures involves engineers and/or technicians putting forward and providing economical designs that have capacity to develop structures against collapse given a return interval of a Tsunami event.

Collapse and failure although disastrous to the regional economy may be unavoidable. Firstly, due to lack of funds to invest in programs and secondly, if the cost to repair or replace the number of structures which are to be hit by a tsunami are less than building structures strong enough to survive the damage in the first place. However if the do-nothing proposal is adopted it is essential that alternative mitigation techniques are considered so the overall aim of reducing risks (loss of lives and livelihood) can still be achieved.

Following the tragic event of the 2004 Indian Ocean Tsunami many proactive strategies including implementing building guidelines and running shelter programs have emerged as part of long term efforts to repair and rebuild structures. From an evaluation of current rebuilding strategies it seems that the majority of these programs rather than being predominantly based on strengthening structures, focus on providing humanitarian responses. Reasons for this currently being the case could be because the role of the structural engineer in alleviating poverty is a relatively new concept; that Tsunami struck nations cannot wait for engineers and technicians to develop strategies based on strengthening structures; and engineered designs in most cases are more expensive than non-engineered design.

Achieving humanitarianism in disaster struck regions, although a key objective should be allied with engineering based regulated shelter programs and effective building guidelines, to achieve greater long term benefits.

6. CONCLUSION

This paper has explored the capacity for structural engineering knowledge to be adopted to inform coastal communities surrounding the Indian Ocean of remedial actions that can be adopted to strengthen structures and as a result mitigate the risks (loss of live, livelihood and damage to assets) associated with multi-hazard disasters.

Despite the existence of methodologies, formulae and engineering knowledge which is already being implemented in some regions of the world to mitigate the risks associated with multi-hazard disasters, engineering and socio-economic challenges have inhibited the application of such programs in the Indian Ocean Region. With the absence of quantitative numerical models and historical data along with high levels of poverty, population growth and conflicting socio-economic challenges, many obstacles in mitigating risks through structural design still need to be resolved.

However, despite these obstacles the introduction of pro-active strategies such as introduction of building guidelines and structural considerations in shelter programs illustrate the potential and enthusiasm of countries surrounding the Indian Ocean region to adopt structural design as part of a holistic approach to disaster reduction in the Indian Ocean Region. This holistic approach should incorporate disaster reduction strategies that utilize several mitigation techniques such as warning systems, education awareness and evacuation plans.

In developing this holistic approach it must be recognized that reduction based programs and strategies, in particular through building design, can only reduce losses for a known return period and magnitude, and that loss of life, livelihood and severe damage is unavoidable in unpredictable extreme events. Furthermore, these mitigation techniques once implemented require continual monitoring and should be updated to meet the needs of the community against the risks associated with potential multi-hazard disaster loadings.

7. GLOSSARY

v = velocity

ρ = density of water (salt = $10.07 \text{ kN} / \text{m}^2$)

g = gravitational acceleration ($9.81 \text{ m} / \text{s}^2$)

h = inundation depth (m)

z = height of relevant portion from ground level (m)

U_p = component of velocity of flood flow perpendicular to the wall (m/s)

V = volume of the building inundated by the Tsunami (m^3)

w = weight in the object (kN)

t = duration of impact

C_d = drag coefficient

A = projected area of the body normal to the direction of flow (m^2)

u = velocity of flow relative to the body (m / s^2)

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