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TSUNAMI RESISTANT DESIGN (TRD)

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ABSTRACT— Presently no authentic guidelines are available for TRD and it is very urgent requirement to draft new code for tsunami load. Here is an initiation to guide for designing of superstructure in the tsunami prone areas. This paper is also a helpful document for drafting a code and giving guidelines for Tsunami Resistant Design.

Paper describes a new concept to draft a code on Tsunami. This paper is giving guidelines only on Tsunami Resistant superstructure Design. After giving present availability of code guidelines on tsunami in the beginning, some important forces for tsunami like Drag force (Hydrodynamic force), Buoyant force, Impact force, Surge force and Hydrostatic force are discussed with their detail primary equation explanations. After designing any building, it is equally important to made stability check for that design. Stability checks for overturning, sliding, compression (crushing) and tension are also explained with their basic equation explanations. Apart from it some important design guidelines, specifically for tsunami prone areas, are also given with figures for clear understanding. Application of this paper, guidelines for soil condition and sub structure design, can also be made. Again application can also be extended up to formation of complete design process for Tsunami Resistant Design and proposal for drafting a code on Tsunami.

Paper is an extension in the initiated effort by an author of this paper to guide for Tsunami Resistance from Civil Engineering point of view.

KEYWORDS— Tsunami, Tsunami Resistant Design, TRD

I. INTRODUCTION

After tsunami it is very urgent requirement to understand building design process for tsunami resistance. Paper is an effort to help in this matter.

Best time to consider resistance from tsunami to buildings is during the earliest project design stage where the performance objectives and standards are set. These decisions govern the final design and eventual constructions.

Paper describes that how tsunami risks can be mitigated through building design and construction. It describes considerations that affect the design and construction of buildings in tsunami hazard areas, describes available building codes and guidelines relating to tsunami generated forces and stability checks, and describes general advice on an approach to the design of new and retrofit of existing buildings.

II. RECENT SCENARIO

A. Building Codes for Tsunami Design

The design of a building to achieve a particular performance level following tsunami is, the amount of damage, the owner can tolerate and the ability of the building to support its intended uses after tsunami strike depends on an integrated set of decisions that begin with determining the importance of building, understanding the consequences of damage and deciding how much damage can be tolerated.

A performance objective expresses this tolerance. Performance depends on the intensity of the tsunami hazard; the location of the building and its configuration (size, shape, elevations, orientation etc); building codes and standards; choice of structural and finish materials; reliability of utilities; the professional ability of designers and the quality construction.

No Indian Standards contain any requirement for Tsunami Resistant Design (TRD). It is very urgent requirement to include one new Indian Standard for Tsunami Loads. Provision of Tsunami Loads can include buoyant force, Surge force, Drag force, Impulsive (impact) force and Hydrostatic force.

B. Understanding for the Hazard

Intense tsunami forces associated with wave surge can inundate two and three story buildings, create currents in excess of 25meter per second, propel debris weighing tons and scour sand from beaches and undermine foundations. In the same event, sites only one or two kilometer away, or nearby sites at higher elevations may only experience the wetting effects of a very few meter of slow moving water. Differences in the hazard are critical to design, but they are subject to a great deal of uncertainty. The challenge is defining the hazard in terms relevant to building design.

C. Select the Intensity of Design Events

Small tsunamis are less damaging, but are more frequent than more intense events. Very large events may be extremely rare and might not be considered except for critical facilities. The probability of occurrence - or the return interval - describes the frequency and intensity of events. Guidance on selecting event frequency and intensity can be taken from the way other hazards are addressed. Design should consider a tsunami with a recurrence of once every 500 years. Buildings with essential uses and large numbers of hard-to-evacuate-people in areas threatened by near-shore-generated tsunamis should consider larger events that reoccur once every 2,500 years. By designing for a larger event with a longer recurrence interval, the design will consider higher water levels and greater forces.

D. DEFINE PERFORMANCE LEVELS

How a building should perform in tsunami depends on the uses supported by the building during and after the event and the needs and expectations of the owner and occupants. Performance levels describe these expectations in terms of damage and the building’s ability to support occupant activities after a hazard event. The desired performance level combined with the probability and intensity of the event, and the level of confidence that the performance will be achieved are combined to express a “performance objective”.

Following goals could be suggested.

- Protect the public from harm.
- Protect public health (release of contaminates and toxic and flammable materials)
- Provide essential public emergency services (police, fire, and emergency management)
- Provide the infrastructural needed for commerce (access utilities)
- Prevent environmental degradations (release of pollutants)

Following four performance levels are suggested.

Minimum Level

Buildings located, designed, and constructed to this level can withstand hydrostatic and hydrodynamic forces without being moved off their foundation or off site. Buildings might suffer extensive damage from flooding and may not resist the impact of debris, wave break forces, scour, or ground failure. These buildings would meet the minimum standards for other hazards. Occupants of these buildings must be prepared to evacuate off site to be safe.

Safety Level

Buildings located, designed, and constructed to this level should withstand forces from hydrostatic and hydrodynamic (pushing and drag) pressures and debris and wave-break impact. They should have foundations designed in anticipation of scour erosion and saturation. People can evacuate vertically to floors above the level of wave action. Extensive damage could be expected to parts of the building affected by flooding and hydrodynamic and debris impact forces, but structural integrity would be maintained. These buildings would be designed to withstand earthquake shaking, induced ground failure, and fire without significant structural damage. Depending on a building’s height and location, it could serve as a refuge from near source tsunamis.

Reoccupancy Level

Buildings located, designed, and constructed to this level can withstand the same forces as safety level buildings and be occupied and functional within a few weeks after clean up, minor repairs, and restoration of utilities. Meeting this standard would require more stringent location restrictions and choice of flood-resistant materials. Building location and the elevation of the lower floors are critical considerations.

Operational Level

Buildings located, designed, and constructed to this level can withstand the same forces and effects as in the Reoccupancy Level, but must have back-up emergency systems (utilities, etc.) needed to support use of the building immediately after the tsunami. These buildings preferably would be located outside of the tsunami hazard area.

III. TSUNAMI LOADS

A. Drag Force (Hydrodynamic Force):

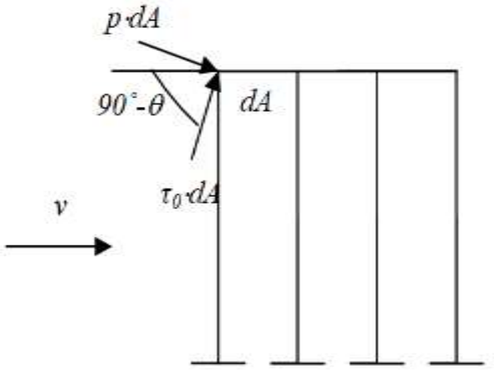

Fig 1 Hydrodynamic Force

Consider any solid structure placed on the way of the flow, which is flowing with a uniform velocity ‘v’ in a horizontal direction. Consider small elemental area dA on the structure. The forces acting on the surface area are

(a) pressure force equal to $\left(p \times dA\right)$, acting perpendicular to surface and

(b) Shear force equal to ($(\tau_0 \times dA)$, acting along the tangential direction to the surface.

Let θ = Angle made by pressure force with horizontal direction.
Now,

$$\begin{aligned}\textit{Drag Force } (F_D) \textit{ on elemental area } &= (\textit{Force due to pressure in the direcion of fluid motion}) + (\textit{Force due to shear stress in the direction of fluid motion}) \\ &= p \cdot dA \cdot \cos\theta + \tau_0 \cdot dA \cdot \cos(90-\theta) \\ &= p \cdot \cos\theta \cdot dA + \tau_0 \cdot \sin\theta \cdot dA \\ \textit{Total Drag Force } (F_D) &= \int p \cdot \cos\theta \cdot dA + \int \tau_0 \cdot \sin\theta \cdot dA\end{aligned}$$

Term $\int p \cdot \cos\theta \cdot dA$ is called the pressure drag or form drag while the term $\int \tau_0 \cdot \sin\theta \cdot dA$ is called the frictional drag or skin drag or shear drag.

The drag force for a structure moving in a fluid of density ‘ρ’, at a uniform velocity ‘v’ are calculated mathematically as

$$F_D = C_D \cdot A \cdot \frac{\rho \cdot v^2}{2}$$

where,
C_D = Co-efficient of drag.
ρ = Density of salt water (1030 kg/m^3)
v = Velocity of flow relative to body (estimated as equal in magnitude to depth in meter of water at the structure at the time of tsunami)
A = Area of structure which is projected area, perpendicular to the direction of flow.

B. Buoyant Force:

The buoyant force on a structural member subjected to partial or total submergence will act vertically through the centre of mass of the displaced volume and calculated form the following equation.

$$\textit{Force of Buoyancy } (F_B) = \rho \cdot g \cdot v$$

where,
ρ = Density of water (1030 kg/m3)
g = Gravitational acceleration (9.8 m/s2)
v = Displaced volume of water (m3)

C. Impact Force:

Consider a flow of water coming from tsunami and strikes a flat vertical surface.
Let,
v = velocity of the jet
A = area of surface perpendicular to tsunami wave

The flow after striking the structure will move along the surface of structure by deflecting through 90˚. Hence the component of the velocity of flow in the direction of flow, after striking will be zero.
The force exerted by the flow on the structure in the direction of flow,

$$Impact\ Force\ (F_I) = F_X = Rate\ of\ change\ of\ momentum\ in\ the\ direction\ of\ force$$

$$= \frac{Initial\ Momentum\ -\ Final\ Momentum}{Change\ of\ Time}$$

$$= \frac{Mass \times Initial\ Velocity) - (Mass \times Final\ Velocity)}{Change\ of\ Time}$$

$$= Mass \times \frac{Change\ in\ Velocity}{Change\ of\ Time}$$

$$F_I = F_X = m \times \frac{\Delta v}{\Delta t}$$

This single concentrated load acts horizontally at the regulatory flood elevation or at any point below it and is equal to the impact force produced by 4500N wt of debris traveling at the velocity of the flood water and acting on a one square meter surface of the structural material where impact is postulated to occur. The impact force is to be applied to the structural material at a most critical or vulnerable location determined by the designer. It is assumed that the velocity of body goes form ‘v’ to zero over some small finite time interval (Δ t)

D. Surge Force (Surge):

Sudden starting and stopping of a flow or a change in the flow rate can cause large pressure variations, and these are significant enough to have to be considered carefully at the design stage.
Surge pressures (or surge force) occur when the velocity of flow is changed on starting or ending of tsunami wave. The magnitude of surge largely depends upon the rate of change of flow and length of tsunami wave.
Pressure intensity due to acceleration or retardation of water may be calculated as below.

$$\text{Retardation/Acceleration of water} = \frac{|Change\ of\ Velocity|}{Time} = \frac{|v - 0|}{t}$$

$$= \frac{v}{t}$$

$$\text{Retarding/Accelerating Force} = Mass\ of\ Water \times Acceleration$$

$$= \rho \times Volume\ of\ Water \times \frac{v}{t}$$

$$Surge\ Force = \frac{\rho \times V \times v}{t}$$

where,
ρ = Density of salt water (1030 kg/m^3)
V = Displaced volume of water (m^3)
v = Velocity of flow relative to body (m/s)
t = Time of contact of tsunami wave with structure in seconds

E. Hydrostatic Force:

Total hydrostatic force on whole surface is given by

$$Total\ Hydrostatic\ Force\ (F_H) = \rho \cdot g \cdot A \cdot \bar{h}$$

where,
g = Gravitational acceleration (9.8 m/s^2)
A = Area of surface in contact for tsunami wave
$\bar{h}$ = Distance of C. G. from free surface
ρ = Density of salt water (1030 kg/m^3)

IV. STABILITY CHECKS:

A. Overturning:

The overturning of the structure takes place when resultant force at any section cuts the base of the structure downstream of the toe. In that case the resultant moment at the toe becomes clockwise (or –ve). On the other hand, if the resultant cuts the base within the body of the structure, there will be no overturning.

The factor of safety against overturning is defined as the ratio of the righting moment (+ve) to the overturning moments, i.e.

$$Factor\ of\ Safety\ =\ \frac{\sum Righting\ Moments}{\sum Overturning\ Moments}$$

$$F.S.=\frac{\sum M_R}{\sum M_O}$$

Since the loads (which were discussed earlier) are known, their moments about the toe can easily be found. Again factor of safety against overturning should be taken around 1.5 as per importance factor of building.

B. Sliding:

Structure will fail in sliding at its base or at any other level, if the horizontal forces causing sliding are more than the resistance available at that level. Resistance against sliding may be due to friction alone, or due to friction and shear strength of the joint. Shear strength develops at the base if benched foundations are provided and at other joints if the joints are carefully laid so that a good bond develops.

If the shear strength is not taken into account, the factor of safety is known as F. S. against sliding. The factor of safety against sliding is defined as the ratio of actual co-efficient of static friction (μ) on the minimum of-efficient of friction required to prevent sliding.
If ∑H is the sum of all horizontal forces causing sliding and ∑(V-U) is the net vertical forces, the sliding factor (tanθ) is given by

$$Sliding\ Factor\ (S.F.)\ =\ \tan\theta=\frac{\sum H}{\sum(V-U)}$$

$$and\ factor\ of\ safety\ against\ sliding\ is$$

$$F.S.=\frac{\mu}{\tan\theta}=\frac{\mu\cdot\sum(V-U)}{\sum H}$$

Co-efficient of friction (μ) varies from 0.65 to 0.75. The factor of safety against sliding should be greater than 1.

Many large structures on sea-shore, shear strength of joint should also be considered for an economical design. The factor of safety in that case is commonly known as the shear friction factor (S. F. F.) and defined by following equation.

$$S.F.F.=\frac{\mu\cdot(\sum(V-U))+b\cdot q}{\sum H}$$

where,
q = Shear strength of joint (usually 14kg/cm2)
b = Width of joint or section

C. Compression or Crushing:

In order to calculate the normal stress distribution at the base, or at any section of a structure let H be the total horizontal force, V be the total vertical force and R be the resultant force cutting the base at an eccentricity of ‘e’ from the centre of the base of width b.

The normal stress at any point on the base will be the sum of the direct stress and the bending stress.

Thus,

$$Direct\ Stress\ =\ \frac{V}{b\cdot 1}$$

$$Bending\ Stress=\pm\frac{M\cdot y}{I}=\pm\frac{6\cdot V\cdot e}{b^2}$$

$$\therefore\ Total\ normal\ pressure\ p_n\ is\ given\ by$$

$$p_n=\frac{V}{b}\left(1\pm\frac{6\cdot e}{b}\right)$$

Evidently the maximum compressive stress occurs at the extreme end and for safety; this should not be greater than the allowable compressive stress f for the foundation material. Hence from strength point of view,

$$\frac{V}{b}\left(1\pm\frac{6\cdot e}{b}\right)\le f$$

D. Tension:

Form the above equations, the normal stress at the heel is

$$(p_n)_{heel} = \frac{V}{b}\left(1 - \frac{6 \cdot e}{b}\right)$$

It is evidently that if e>b/6, the normal stress at the heel will be –ve or tensile. No tension should be permitted at any point of the structure under any circumstance for moderately high structures. For no tension to develop, the eccentricity should be less than e/6. In other words the resultant should always lie within the middle third.

However in case of extra high structures, 230 to 260m, small tension within the permissible limit is generally permitted for comparatively small periods of loading conditions.

V. OTHER IMPORTANT DESIGN CONSIDERATIONS

Following are important design considerations to design a building tsunami resistant.

- Buildings or structures shall be designed to resist the effects of coastal floodwaters due to tsunami. The regulatory flood elevation due to tsunamis is considered to result form a non-bore conditions, except where a bore condition is shown on the flood maps or in the flood study adopted by the country.
- Habitable space in the building structures must be elevated above the regulatory flood elevation by such means as posts, piles, piers or shear wall parallel to the expected direction of flow of the tsunami wave. The factor and effects of flood waters on the structure shall be fully considered in the design.
- Allowable stresses (or load factors in the case of ultimate strength or limit design) for the building materials used shall be the same as the building code provides for wind or earthquake loads combined with gravity loads, i.e. treat loads and stresses due to tsunamis in the same fashion as for earthquake loading.
- The main building structure shall be adequately anchored and connected to the elevating substructure. System to resist all lateral, uplift and downward forces. In wood construction, toe nailing is not allowed.
- Where a building is to be constructed so that the lowest floor is to be elevated above the regulatory flood elevation, the building may be supported on columnar type members, such as columns, piers and in certain cases wall. Clear spacing of support members, measured perpendicular to the general direction of flood flow shall not be less than three meter apart at the closest point. The stilts shall, as far as practicable, be compact and free from unnecessary appendages which would tend to trap or restrict free passage of debris during a flood. Solid walls or walled-in columns are permissible if oriented with the longest dimension of member parallel to the flow. Bracing, where used to provide lateral stability, shall be of a type that causes the least obstruction to the flow and the least potential for trapping floating debris. Foundation supports for the stilts may be of any approved type capable of resisting all applied loads, such as spread footings, mats, piles and similar types. In all eases, the effects of submergence of the soil and additional flood water related loads shall be recognized.

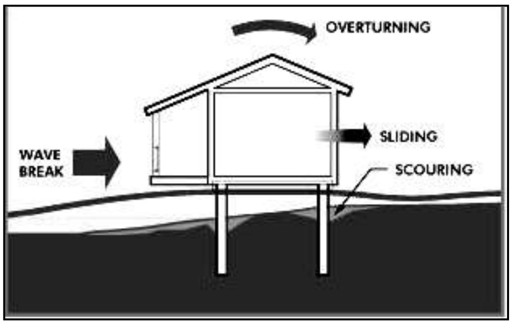

Figure – 2 Forces on structures created by tsunamis

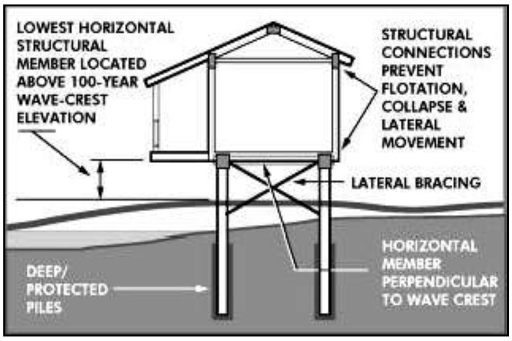

Figure – 3 Design solutions to tsunami effects

- Following points shall be applicable to the buildings on natural terrain-
  - Foundation design shall take into consideration the effects of soil saturation on the performance of the foundation.
  - The effects of flood waters on slope stability and erosion shall be investigated.
  - All utility service lines shall be designed and constructed as provided in the planning and electrical codes.
- Design and construction of new buildings and the retrofitting of existing building should address forces associated with water pressure, buoyancy, currents and waves, debris impact, scour and fire.
- Substantially-built building of concrete, masonry and heavy steel frames are likely to do fairly well in a tsunami unless compromised by earthquake shaking. Wood frame buildings, manufactured housing and light steel frame structure at lower elevations close to the shoreline are likely to fare poorly. However, not every area affected by tsunami urn-up will experience damaging forces. Buildings in these less hazardous areas affected by shallow run-up water depths should survive with repairable damage if well designed and constructed. The forces of currents and breaking waves, fast-moving waterborne debris and scouring currents will exceed the resisting capabilities of most buildings unless the building is built with specific design elements and materials.

VI. CONCLUSIONS

Designing is the responsibility of designer. That is the person, who has to think for safety level, design forces, stability checks, and important design points by considering occupancy, occupants, importance, orientation and position of structure. Here is an effort for design help to the designers for tsunami resistant superstructure design with help of very primary forces. Detail and specific equations can be derived using the practical experiments for various factors on real conditions. Basic forces like drag or hydrodynamic force, buoyant force, impact force, surge force, and hydrostatic force with stability checks for overturning, sliding, compression and tension was explained with their basic equations. Designer has to apply the forces by considering the requirements.

VII. APPLICATIONS

Here are some primary guidelines to design a superstructure only. This is very small effort to guide for tsunami resistant superstructure design. Similar guidelines for soil condition and sub structure design can also be made. Above this, it is equally important to form a standard design process for complete Tsunami Resistant Design (TRD) of structure by considering various factors and conditions. Effort is also needed to form a proposal for drafting the standards for complete tsunami resistant design. Though, the initiation of effort was made by an author of this paper from earlier paper titled as “Planning of Tsunami Hazard Areas”. This effort ends only when complete design standards for tsunami resistance can be developed which contain building (super and/or sub structural) design, planning of areas, etc.

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