Building Foundation Instability Induced by Tsunami Scour

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INTRODUCTION

Understanding the role of tsunami-induced scour in building foundation instability can allow for the proper design of buildings located in areas prone to tsunami events. The process of tsunami scour around building foundations reduces the bearing capacity of the soil to support loading, lateral resistance and loss of soil-foundation friction (i.e. piles). Scour can cause loss of material around a foundation, due to increased pore pressure within the soil and removal of the soil during the tsunami, resulting in reduced bearing capacity of the soil (Macabuag et al., 2018). During the 2004 Indian Ocean Tsunami and the 2011 Great East Japan Earthquake and Tsunami, three similar failure modes of building foundations were experienced, namely overturning, sliding and bearing (scour) failure (Macabuag et al., 2018). According to Wright (2015), shallow foundations such as strip, slab or pad are vulnerable to erosion of surrounding soil causing scour during a tsunami. The present paper discusses the application of the scour depth predictive model of Nicholas et al. (2016) and the development of a Relative Risk Index for future design of building foundations accounting for tsunamis.

SHALLOW FOUNDATION FAILURE DUE TO SCOUR

During the two aforementioned tsunami events both shallow and deep building foundations were affected by tsunami-induced scour. Scouring of soil alters the soil stress history therefore changing the stiffness and strength of the soil (He et al., 2019). He et al. (2019) also noted that scour increases the over-consolidation ratio and reduces the shear strength of the undrained soil. This can weaken undrained soils with potential foundation failure while drained soils can undergo from deep scour failure (Wright, 2015).

Figure 1 - Apartment block scouring at the seaward end in Yuriage, Japan due to the 2011 Tohoku tsunami (Fraser et al., 2013)

Soil weakening following a tsunami wave can result in foundation failure for shallow foundation buildings, mainly due to bearing failure which causes undermining and subsequently, tilting, as seen in Fig. 1 (taken from Fraser et al., 2013). Tsunami scour can cause the reduction in foundation depth. As a result, loading from the building and any other imposed loads can no longer be transferred into the ground, resulting in the collapse of the building, either immediately or over time.

ANALYSIS OF THE FAILURE MECHANISM FOR BUILDING FOUNDATIONS

The main type of failure in shallow foundations is bearing failure, which results in undermining, tilting and rotation. Figure 2 illustrates the progressive failure of a spread foundation.

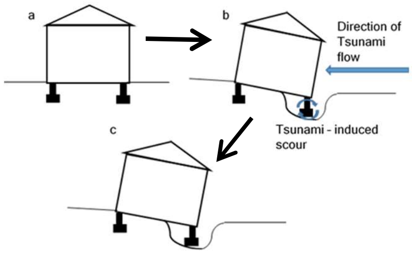

Figure 2 - (a) Foundations pre-tsunami inundation, (b) Foundations experiencing scour during a tsunami wave and (c) Foundations post-tsunami inundation. After (c) the foundations are fully undermined

The severity of failure of the foundations is dependent on the foundation depth, scour depth and its extent. In the 2004 Tohoku tsunami, less severe failure (light undermining and tilting) was found in areas where there was shallow localized scour around the foundations, small scour extents and where foundation depths were equivalent or deeper than the scour depth (Fig. 1). More severe failure such as complete collapse or rotation of foundations was observed in areas where there was deeper scouring, wider scour extents and where foundation depths were relatively shallow compared to depths of scour holes (Fig. 3).

Figure 3 - The failure mode of building foundations shows tilting leading to rotation and collapsing due to a large scour hole

FORECASTING FUTURE FOUNDATION FAILURE

Figure 4 shows that foundations with deep scour holes in comparison to the design foundation depth or existing foundation will experience some form of foundation failure.

In order to construct foundations to withstand tsunami-induced scour, it is imperative to predict potential scour depth. For this purpose, adequate scour predictive models suggested by Nicholas et al. (2016) such as the Tonkin et al. (2003) model and Nicholas et al. (2016) model can be used.

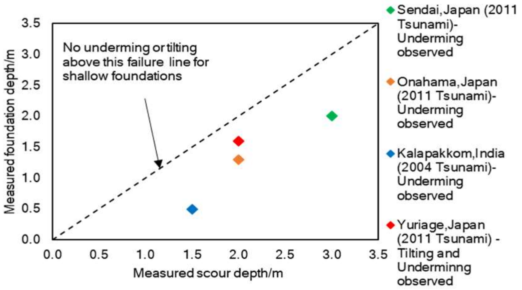

Figure 4 - Measured foundation depth against measured scour depth (bearing failure causing tilting/undermining)

RISK ASSESSMENT MATRIX FOR SHALLOW FOUNDATION FAILURE

Risk assessment should incorporate the use of output from a scour predictive model (e.g., Nicholas et al., 2016) and the design or existing depth of the foundation being assessed. Using the conservative outlook from Fig. 4 the following definitions can be used concerning foundation failure due to tsunami scour using the risk matrix generated below:

- Condition (1) - No Failure:

$$\frac{\text{Foundation Depth (FD) (m)}}{\text{Tsunami Scour Depth (TSD) (m)}} \geq 1 \text{ (unlikely failure)}$$

- Condition (2) - Failure:

$$\frac{\text{Foundation Depth (FD) (m)}}{\text{Tsunami Scour Depth (TSD) (m)}} \leq 1 \text{ (likely failure)}$$

The above inequalities can be visualized in a risk matrix diagram showing high to low risk zones (Fig. 5). As seen from conditions (1) and (2), buildings are identified as at high risk when there is a prediction or potential of deep scour and the building has a very shallow foundation depth (a ratio of less than 1). Buildings are identified as at low risk when there is a prediction or potential for shallow scour depth but the foundation depth is deeper (a ratio greater than 1 is achieved).

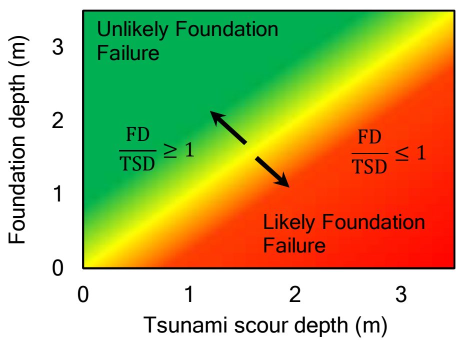

Figure 5 - Relative Risk Matrix

MITIGATION OF BUILDING FOUNDATION FAILURE

Risk assessment for building foundations can help to identify whether intrusive methods of mitigation can be undertaken to reduce scour. Our risk matrix can be used to identify vulnerable foundation structures and determine mitigation techniques. The mitigation techniques ultimately selected will be influenced by the coastal characteristics and societal demands. One such mitigation recommendation is the use of deep piled foundations near the coastal belt where tsunami-induced scour hazards are have occurred and where non-cohesive or soft cohesive soils are identified (Wright, 2015). Non-cohesive or soft cohesive soils give rise to deep scour. However, an alternative recommendation would be to use deep non-piled foundations as piled foundations can face complications due to soil liquefaction washing away soil. Such loss of soil can result in loss of skin friction of the pile or pile group resulting in reduced pile resistance and causing buildings to overturn during the tsunami event. Also, implementing counter measures such as reducing the width of buildings towards the seaward end and increasing the surface roughness around the corners of the building can reduce scour and hence potentially mitigate the failure of building foundations (Nicholas et al., 2016).

CONCLUSIONS

The process of tsunami-induced scour can lead to major bearing capacity failure in building foundations. Undermining of foundations sometimes results in tilting which was the most common scour-induced failure mode we found from the analysis of data for shallow foundations for both the 2004 and 2011 tsunami events. Mitigation measures such as deepening foundation depths, based on the use of predictive scour depth models such as Nicholas et al. (2016) can be used to redesign building foundations in order to withstand future tsunami events. Furthermore, a Relative Risk Matrix can be used to assess the vulnerability of existing foundations as well as for the design of new foundations suitable for local conditions.

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