Numerical Investigation on the Impact Resistance of Reinforced Concrete Pier

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Abstract. This paper presents a numerical investigation on the impact resistance of reinforced concrete pier. The impact resistance of reinforced concrete pier was determined by simulating the impact from floating log onto a pier during flood, with and without scour. A single pier of 0.9 m diameter and height of 4.0 m was modelled based on the actual working drawing by Public Works Department of Malaysia. Concrete grade for pier varies from grade 30 to grade 150. The log impacting on pier resembles the impact load of 2.0 tonne as recommended in the design guideline. The numerical analysis is conducted with the aid of ANSYS Explicit Dynamics R14 software. Damage index was used to describe the fracture state of the pier. The flood velocity and impactor properties incorporated in the model were based on flood velocity studies and available hardwood in Malaysia. The results indicated that all the impacted pier exhibits local damage in the form of penetration and scabbing. The critical velocity for pier without scour ranges from 1.75 m/s to 2.25 m/s compared to from 1.75 m/s to 3 m/s with scour. The impact resistance of reinforced concrete pier is found to be insignificantly affected by pier concrete grade.

1.0 Introduction

Bridge is often regarded as the most expensive component of a transportation network [3]. Natural disaster, for example flood may cause significant damage to this structure, causing failure of the transportation system beside economic losses. Damage of bridge due to flood were often caused by erosion of the soil under pier and abutment footings i.e. scour, overturning water on the deck besides impact load from the floating debris on the pier, deck, piles and abutment [71]. Bridge failure is hardly resulted from calculations errors, but underestimation on effects of scour and or accumulation of ice or debris on to the bridge, simultaneously applying horizontal forces to the structure [2]. In Malaysia, the impact load from floating debris, particularly log imparted on the bridge pier has been determined as the cause of bridge failure in numerous flood occurrences such as listed in Table 1.

Table 1: Reported cases of bridge failures due to floating log in Malaysia

| Location | Date       | Source                |
|----------|------------|-----------------------|
| Kampung Sungai Pemberian, Sungai Lebir, Kelantan | January 2016 | Astro Awani [9] |
| Sungai Nenggiri, Kampung Pulau Setelu, Kelantan   | December 2014 | Utusan Malaysia [20] |
| Kampung Landai Melaka, Sik Kedah                  | December 2012 | Utusan Malaysia [21] |
| Kampung Bendang Man, Baling, Kedah                | August 2010   | MStar [16]           |
| Kampung Sempeneh Cempaka, Batu Kurau, Perak       | 2008          | Warta Utara [22]     |
Recent major flood in Kelantan in December 2014 has caused a large number of floating log to impart load on bridge pier, causing bridge failure at Kampung Pulau Setelu at Kilometer 31.5, Jalan Gua Musang-Jeli, as shown in Figure 1.

Figure 1: Bridge failure due to impact load from floating log at Gua Musang, Kelantan in December 2014 [20]

A review on existing bridge specifications showed that the impact load due to floating log (termed as ‘drift’) is considered under provision of debris impact load. The impact load due to debris is often discussed in term of resulting scouring evolution, drift accumulation and effect of the impactor properties (i.e. drift) to the impact resistance of the pier. Failure of bridge piers were still reported although there were some standards and guidelines which consider the impact force in the design. There were very few studies which explain the mechanism of floating log impact to the bridge pier. There are also lack of study discussing the influence of the pier properties to the impact resistance of the pier subjected to drift load, either by laboratory or by finite element modelling. This research aims to determine the impact resistance of pier by simulating the impact from floating log onto a pier during flood, taking into consideration both scour and non-scour effect. The interest is focused on the ability of pier with different concrete grades to withstand the impact load travelling at various velocities via the measurement of the damage index. The objective of this study is to determine the critical velocity of impactor for reinforced concrete pier with and without scour, to study the influence of different concrete grades to the impact resistance of pier and to investigate the effect of scour on the impact resistance of pier. This study will model a single pier with the size of 0.9 m diameter and height of 4.0 m. The size, dimension and reinforcement detailing are taken from the actual working drawing based on Public Works Department bridge design guidelines 1985[17]. The log impacting on pier resembles impact load of 2.0 tonne as recommended in the design guideline. The location of the impact can occur almost anywhere along the pier’s shaft depending on the flood level. However, for this study, the location is set to be 2.0 meter from the top of the pier. This location is expected to give the worst-case scenario in terms of the damage (i.e. the location for impactor to hit the pier, at which will produce the lowest value of critical velocity). The numerical analysis is conducted with the aid of ANSYS Explicit Dynamics R14 commercial software. Damage index was used to describe the fracture state of the pier.

2.0 Modelling parameters
2.1 Pier, pile cap and pile
A circular pier with diameter 900 mm, 4m high of grade 30 is modelled. The main reinforcements are 12 nos. of high tensile bar with diameter 32 mm (12Y32) and the link used are high tensile bar of size 12 mm with 75 mm spacing (Y12-75). 4 nos. of square piles of size 300 mm x 300 mm and grade 45 were used. The pile cap size is 1800 mm width, 1800 mm length and depth 675 mm. For steel reinforcement, idealized stress strain data for high tensile reinforcement was used in the Engineering
Data interface in ANSYS Explicit Dynamics, which is based on the idealized stress versus strain curve in British Standard 8110 Part 1:1985 [12].

2.2 Log
The data on local hardwood is gathered to simulate the impact of log available in Malaysia. Choice of the log type to be modelled was based on maximum available density of the hardwood. Maximum density of log is expected to provide the worst-case scenario of impact load. The online data by Malaysian Timber Council official website showed that the maximum density was 980kg/m$^3$ for hardwood type Cengal and Kedondong [13]. The selection for type of hardwood also depend upon available mechanical property that was required as an input to the Engineering Data interface in ANSYS Explicit Dynamics. Modulus of Elasticity and Poisson Ratio for hardwood of type Kedondong are 12900 MPa and 0.63 respectively [13]. The log impactor modelled in this study is based on Public Works of Department Malaysia design guideline [17], which the mass of the log is taken as 2 tonne (2000 kg).

2.3 Impactor velocity
Velocity at which the log moves was taken as equal to velocity of the river flow during flood. Previous studies were referred to determine the range of flood velocities in Malaysia. These velocities would be used to simulate the velocity at which the log moved in ANSYS Explicit Dynamics simulation. Several researchers have established hydrodynamic models to establish flood velocities at various rivers at Malaysia [1][4][14][19]. Based on the studies, the range for flood velocities was decided from 0.5 m/s to 15 m/s. The simulation used the minimum velocity of 0.5m/s with an interval of 0.5m/s until the damage index algorithm in ANSYS reaches value of 1.

3.0 Numerical modelling
In this study, the non-linear dynamic FE simulation employed the ANSYS Explicit Dynamics Release 14.0 software package developed by ANSYS Incorporated. The solution method employs the Lagrange formulations in the ANSYS solver and the Concrete Model embedded in the ANSYS Explicit Dynamics to represent the material model for pier. Pier is modelled as a three-dimensional model. All the relevant data such as scour depth, pier details, log properties and flood velocities were obtained prior to modelling. The mesh sensitivity analysis was carried out in order to determine the mesh size. The mesh size is then assigned to the model for actual analysis. The critical impact velocity is determined from the result. The effect of concrete grade and scour to the impact resistance of the pier were also analysed.

3.1 Material and Engineering Properties
The Riedel-Hiermaier-Thoma (RHT) Concrete Strength Model in ANSYS Explicit Dynamics was adopted to model the reinforced concrete pier. Since the pier incorporates concrete grade 30, interpolation has been carried out to determine the values for three other different parameters namely compressive strain rate ($\alpha$), tensile strain rate component ($\delta$) and shear modulus for concrete grade 30, 50, 80, 120 and 150 used in this study. Other parameters were consistent as normalized values were utilized. Similar computation was made to assign concrete grade 45 to the piles.

3.2 Scour depth
Determination of scour depth is then carried out based on ratio of scour depth/pier width established by O’Connor [15]. For cylindrical pier, the scour depth is taken as 1.5 times the diameter of the pier. The overall scour depth is computed as 1350 mm and the scour at pile is determined as 675mm.

3.3 Mesh sensitivity analysis
Mesh sensitivity analysis was carried out to study the mesh element sizes to determine its effects on the simulation. Five different mesh sizes were used i.e. 120, 100, 80 mm, 60 mm and 40 mm. The end
time was set at 0.08 sec. The velocity was set at 2 m/s, concrete grade 30. The result of the mesh sensitivity analysis (mesh size) was used as the mesh size for the actual analysis. The deformation of the pier and the computational were set as the references. The results were plotted using double axes graph and discussed accordingly.

3.4 Proposed damage criteria: Damage Index

ANSYS Explicit Dynamics defined Damage Index as the ratio between the initial and reduced resistance capacity of a structure. The value could be used to predict the current strength surface state of the material upon impact. The governing equation is embedded in ANSYS algorithm based on the geometric strain and the shear induced cracking as shown in the following equation [23]:

\[
D = \sum \frac{\Delta \varepsilon_p}{\varepsilon_p^{fail}}
\]

\[
\varepsilon_p^{fail} = \text{MAX} \left( D1(P^{*} - htl^{*})^{D2}, \varepsilon_{p,min}^{fail} \right)
\]

\[
htl^{*} = -\frac{f_t}{f_c} - \frac{f_t}{f_c} \times \psi_d \left( \frac{f_t}{f_c} - \frac{f_t}{f_c} \right)
\]

(1)

Where:

- \(D\) = damage index (ranging from zero to unity),
- \(D1 & D2\) = damage constants,
- \(\varepsilon_p^{fail}\) = pressure dependent plastic strain to failure,
- \(\varepsilon_{p,il}\) = minimum strain to failure (complete damage at low pressure),
- \(htl^{*}\) = normalised hydrodynamic tensile limit,
- \(f_t/f_c\) = normalised tensile strength and \(f_{sfc}\) = normalised shear strength.

Since there were no established criteria on describing the damage on the pier, following criteria were proposed as the guideline which are concrete disintegration and damage index equal to 1. Pier is said to be damaged as there is concrete disintegration i.e. damage index is not equal to zero as shown in Figure 2(a). Damage index was set by the algorithm to describe fracture state of the pier material. Damage index equal to 0 represents a totally intact material. Damage index equal to 1 indicated that part of the material of pier was fully fractured as shown in Figure 2(b).

![Figure 2: Pier damage criteria a) Pier concrete disintegration b) damage index equal to 1](image)
3.5 Assumption

Several assumptions have been made in this study. Pier is assumed to be new i.e. no deterioration has taken place. Corrosion in reinforced concrete structure particularly chloride-induced corrosion of steel reinforcement reduced the impact resistance capacity [10]. In this the pier was assumed to be in perfect condition therefore no corrosion has taken place at the steel reinforcement of the pier which may affect the impact resistance. The log impactor was assumed to move at the same velocity as the velocity of flood water. In reality, fluid drag and inertia would cause higher force than which can be predicted by Newton’s second law of motion ($F = ma$), hence may decelerate the log. The log was assumed to be floating and moved in uncongested manner. Unless the wood is clogged by water, it is typically less dense than water, causing it to float [9]. Braudrick et al. [6] studied the dynamics of wood transport in streams through a series of flume experiments and observed three distinct wood transport regimes: uncongested, congested and semi-congested. During uncongested transport, logs move without piece-to-piece interactions and generally occupy less than 10 per cent of the channel area. In congested transport, the logs move together as a single mass and occupy more than 33 per cent of the channel area. Semi-congested transport is intermediate between these two transport regimes. The log was also modelled to impact the pier at its end, based on laboratory experiment by Haehnel et.al [8]. The author showed that the maximum impact force was associated with a log striking a rigid structure with its end (with the long axis of the log parallel to the flow direction and normal to the structure face, i.e. 0° collisions). It is worth mentioning that oblique and eccentric collisions reduced the maximum impact load in a predictable and consistent manner. The impactor was assumed to be rigid, i.e. the stresses built up in the impactor due to the impact is neglected. There was no dispersion of the impact load, which means all the impact energy was transferred to the pier, deck and substructure. The self-weight of the bridge superstructure, which exerted axial load to the pier, was not considered. Compressive force (i.e. axial load) will resist horizontal load and will not form the worst condition for the analysis of impact. However, the buckling effect due to axial load to the pier was not mobilized. The established model is shown in Figure 3.

![Established geometry model for pier](image)

4.0 Results and discussions

As the log stroke the pier, the impacting body kinetic energy transformed partially to strain energy within the pier and dissipated partially through local plastic deformation and friction. From the simulation, the impacted pier exhibited local damage in the form of penetration and scabbing. However, more severe local damage i.e. perforation and punch type shear failure were observed as the velocity went as high as 15 m/s.
4.1 Mesh sensitivity analysis
Figure 4 shows the result of mesh sensitivity analysis. From the result, the computational time increased as the mesh sizes decreased. The differences in term of the deformation values were found to be insignificant. However, the computational time (denoted by CPU time in the graph) increased significantly when small mesh sizes were used. Although coarse mesh can be used but it was decided to use the 40 mm mesh size to analyse the damage on pier. The mesh is uniform throughout the elements. The analysis of the other bodies i.e. pile cap, pile and impactor were carried out using 60mm mesh size. The mesh selection is based on the fact that there was no experimental data on which the finite element simulation could be validated. Use of smallest size mesh size could increase the accuracy of the result. The computational time was reasonable for mesh size 40mm used at the pier, by which the average computational time were 8 to 10 hours per sample. Use of 60mm size for other bodies was considered to minimize overall computational time.

![Figure 4: Mesh sensitivity analysis showing variation in the deformation and computational time versus element size.](image)

4.2 Damage index and critical velocity for reinforced concrete pier without scour effect
The damage index obtained for reinforced concrete pier without scour effect subjected to varying impactor velocity is shown in Figure 5(a). The simulation showed that low impactor velocity (0.5m/s) only affected low grade pier (i.e. grade 30 and grade 50) while the pier of higher grade 80,120 and 150 was not affected. The significant damage started at velocity 1m/s for both low grade piers (i.e. grade 30 and 50) while material for piers grade 80 and 120 were slightly fractured. The simulation also showed that the reinforced concrete pier without scour totally collapsed at different velocity as the concrete grade varies. The velocity at which the damage index equal to 1 i.e. critical velocity is shown in Figure 5(b). From the chart, it was observed that the critical velocity at which part of the pier material was fully fractured increased as the concrete grade increased. The maximum critical velocity obtained was 2.25m/s for pier grade 150, while the lowest critical velocity was 1.75m/s for both piers of grade 30 and grade 50. The increase in critical velocity was only 0.5m/s for 120MPa increase in concrete grade, or 0.0042m/s for every 1MPa increase in concrete grade. The impact resistance of reinforced concrete pier without scour was not significantly affected by the concrete grade/ compressive strength [11] [7]
4.3 Damage index and critical velocity for reinforced concrete pier with scour

The reinforced concrete pier with scour were fully fractured at top of pier and at the end of piles, where the rigid fixity is assigned for all grades of concrete. However, the damage is more severe as the grade increases. The damage index for reinforced concrete pier without scour effect is summarized in Figure 6(a). The simulation has also shown that low impactor velocity (0.5m/s) insignificantly affected all piers. There is no relationship between the concrete grades and the damage index at this velocity. The damage index for grade 50 and 120 were equal while for other grades, it was either higher or lower. The significant material fracture for pier grade 30 started at velocity 1m/s. Pier grade 50 showed significant increase in damage index at velocity 1.5m/s. Higher grade piers damage indexes were slightly above +0.25 at this velocity. The velocity at which the damage index equal to 1 i.e. critical velocity is shown in Figure 6(b).

From the chart, it was observed that the critical velocity at which the part of the pier material was fully fractured increased with the increment of the pier concrete grade up to grade 120 only. The maximum critical velocity obtained was 3.0m/s for piers grade 120 and 150, while the lowest critical velocity was 1.75m/s for pier of grade 30. The range of critical velocity for this reinforced concrete pier under scour up to 1.5 times its diameter ranged between 1.75m/s - 3.0 m/s. The impact resistance of reinforced concrete pier under scour was insignificantly affected by pier concrete grade/ compressive strength.
4.4 Comparison between impact resistance of reinforced concrete pier with and without scour

Results has shown that part of the pier material were fully fractured at different critical velocity for both scour and non-scour exposure. The critical velocity for piers subjected to scour and without scour is shown in Figure 7. At grade 30, the critical velocity for both scour and non-scour are the same, i.e. 1.75 m/s. However, as the grade increased, the critical velocity for pier subjected to scour also increased up to grade 120. Part of pier material subjected to scour achieved full fracture at higher impactor velocity compared to pile without scour. This implies that the impact resistance of the reinforced concrete pier under scour effect is higher compared to impact resistance of non-scour pier.

![Figure 7: Critical velocity for reinforced concrete pier under scour and without scour](image)

Theoretically, the impact resistance of pier under scour is expected to be less than the impact of pier without scour due to the increase in the fixity length. The conflicting findings may due to the disadvantages of using damage index as failure criteria. The damage index equal to one only indicates full fracture of the material, but does not indicate the severity of the damage on the structure. At critical velocity, pier of grade 30 may exhibit less damage distribution compared to pier of grade 120 as shown in Figure 8.

![Figure 8: Isometric view of the damage distribution at critical velocity for pier under scour of grade 30 (left) and grade 120 (right)](image)

The damage index also lack feature to describe the state of structure after impact, i.e. either only cracked or totally collapse. For example, damage index one for pier grade 150 for non-scour cases occur at velocity 3.00m/s. However, as the velocity increased up to 15m/s (based on flood velocity...
range in this study), it is shown that the pier is totally displaced, and the concrete material disintegrated as shown in Figure 9.

![High damage index area](image1)

![High damage index area](image2)

**Figure 9:** Pier grade 150 having damage index equals to one at velocity 2.5m/s (left) and 15m/s (right).

Incorporation of this additional criteria could be able to more accurately described the behaviour of pier under scour or non-scour environment. The assumption made during the modelling may also contribute to the findings. This study is an early work to establish the pier behaviour during impact, in which modelling scope is limited to pier and other substructures (i.e. pile cap and pile), without taking into consideration the superstructure. Unequal distribution of stiffness and impact load location are also another factor which may influence the findings. The effect of stiffness to the resultant critical velocity is illustrated in Figure 10. Pier A is the initial case of pier without scour, with impact load at midpoint (i.e. 2.0m from top of pier). Pier D showed the pile with additional scour depth of 1.35m to the pier, therefore the overall length of pier subjected to the impact load becomes 5.375m. The load location was maintained at 2.0m from top of pier, therefore the impact load did not hit at midpoint. Pier B showed the equivalent length of actual pier and scour depth, however, the stiffness was made equal with Pier A. In pier C, the stiffness also was equal to Pier A, but the location of the impact load was fixed at midpoint, i.e. 2.675m from top of pier.

![Unequal distribution of stiffness: Critical velocity](image3)

**Figure 10:** Effect of stiffness and impact load location

From Figure 10, it is shown that the critical velocity for Pier A (2m/s) was lower from Pier D (3m/s). Additional points with fixed rigidity in Pier D contributed to stiffer pier. The stiffness was made equal by comparing Pier A (without scour) with Pier B (with scour). It was found out that with equal stiffness, the critical velocity obtained was equal (2m/s). This showed that stiffness of the model did
influence the impact resistance. However, the load location was different. Comparison was then made between Pier A and Pier C, at which the location of impact load was at midpoint. The result showed that when load acted at midpoint, the resultant critical velocity for pier with scour (Pier C) was lower (1.95m/s) compared to Pier without scour (Pier A, with velocity 2.0m/s), provided that the stiffness were equal. Comparison between Pier B and Pier C showed that critical velocity for load acting at midpoint was 1.95m/s (Pier C) while it was higher at other location i.e. 2.0m/s (Pier B). This finding supported the initial assumption of the modelling that load acting at midpoint will give the worst condition, i.e. the lowest critical velocity along the pier length.

5.0 Conclusion
This study has demonstrated the impact resistance of pier under scour and non-scour environment. The influence of pier property such as concrete grade to the impact resistance of the pier was studied through finite element simulation. The range of critical velocity for pier without scour is from 1.75m/s to 2.25m/s while for pier with scour, the critical velocity is from 1.75m/s to 3.0m/s. The impact resistance of reinforced concrete pier without scour was found to be insignificantly affected by the concrete grade/compressive strength. For pier with scour, the critical velocity increased with the increase of the pier concrete grade up to grade 120 only. The impact resistance of reinforced concrete pier under scour was also insignificantly affected by pier concrete grade/compressive strength. Pier subjected to scour was found to collapse at higher impactor velocity compared to pile without scour. This implies that the impact resistance of the reinforced concrete pier under scour effect is higher compared to impact resistance of non-scour pier. Theoretically, the impact resistance of pier under scour was expected to be less than the impact of those piers without scour. The conflicting findings may due to the lack of features of damage index as failure material i.e. lack features to describe damage severity and state of structure after impact, assumption made during the modelling i.e. type of fixity, partial modelling of the system and unequal distribution of stiffness and impact load location.

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