# Experimental investigation and finite element modelling of the effects of flow velocities on a skewed integral bridge

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Over the past 30 years, there has been an increasing need to replace the current stock of bridges in Malaysia, since modern bridge systems have a lower life cost. In particular, the huge maintenance cost incurred for the expansion joints and bearings of conventional bridges has been a major concern for local state councils and authorities. The government has also acknowledged the exceptional rise in maintenance costs, the concurrent decrease in highway revenues, and the serious impact on future highway construction projects. Bridges of total lengths less than 60 m are more economical and cost-effective if designed as integral bridges having full structural continuity and smaller numbers of expansion joints. In view of these requirements, integral bridges have become feasible alternatives, and a dramatic increase has been noted in the construction of such bridges in Malaysia.

However, since the use of integral bridges is still relatively new in Malaysia, design factors relating to the effects of natural hazards and local weather as well as environmental conditions are unavailable and yet to be established. One of these factors is the effect of floods on integral bridges, which is of prime concern to bridge designers. Since the 1920s, the country has experienced major floods during seasonal monsoons, causing a large concentration of surface-runoff that exceeds the capacities of most rivers. States located on the east coast of Peninsular Malaysia such as Kelantan, Terengganu, Pahang and Johor are badly affected by these massive seasonal floods.

It is only since the early 1990s that flash floods have become a concern in urban areas; these flash floods are perceived to be the most critical of flood types. Hence, detailed investigations on the effects of floods on integral bridges are vital. Flash floods are the most dangerous kind of floods, because they combine the destructive power of a flood with incredible speed and unpredictability. Examining flash floods and scouring effects, Tregnaghi et al. [25,26] found that clear-water boundary conditions can be extended to sediment-supply tests if specific supply input conditions hold. Moreover, experiments show that the ratio between the final scour depth and the potential scour depth at a bed sill for a given hydrograph can be estimated as a function of the identified temporal parameter.

The general aim of the study was to investigate of the effects of floods and scour on a skewed integral bridge. The specific objective of this study was to investigate the behaviour of scour and the relationships between scour depth and structural behaviour of skewed integral bridge. The other parameters include time evolution of scouring, loading, strain and displacement at different locations of the bridge. Although time evolution for scouring data was taken, the main focus of the experimental work and modelling investigation was to compare the maximum scour after 24 h.

The developed model consists of a single span integral bridge that focuses on the local scour on the abutments. Previous researchers have categorized abutment as short and long based on the observed flow features. Kwan [14] investigated the effect of local scour on short abutments. The study showed that the local scour on short abutments and piers are similar. The principle features of the flow are the down flow ahead of the abutments, a principal vortex, and wake vortices. Many articles have been published on matters pertaining to scour on conventional bridge foundations [6,7,15,16,19,20,22,23]. Local scour studies focusing on the effects of time have been published by Kwan [14] and Melville and Chiew [21]. Akib et al. [1] concluded that local scour on a double-row pile integral bridge is higher than on a single-row pile integral bridge in a two-stage channel. Scours on pier and pile groups were well researched and documented by Kambekar and Deo [13], Sumer et al. [24], Ashtiani and Beheshti [3], and Coleman [9]. Martin-Vide et al. [18] examined the problem related to the interaction of two widths (pier and piles) that were set at different elevations with respect to the riverbed; a width-weighting method was recommended due to greater scouring when the riverbed is closer to the base of the pier. Akib et al. [2] proposed a countermeasure to reduce scour on a semi-integral bridge pier using Epipremnum aureum.

Scouring around a submerged vertical cylinder in a steady current was studied both experimentally and numerically by Zhao et al. [30]. A three-dimentional finite element model was developed for local scouring simulation. They found that the simulation modelling results are smaller than the experimental results (around 20%). Huang et al. [12] investigated the scale effect on turbulent flow and sediment scour using the three-dimentional computational fluid dynamics model. The physical scale and the boundary velocities were setup for the small-scale model based on Froude similarity law. The results were compared for two cases: small-scale model and full-scale model. The study shows that ignoring Reynolds similarity in physical modelling may result in errors for scouring in large bridge piers. They show also that not all of the physical quantities could be provided; some of these quantities in a turbulence flow are difficult to measure such as the vortex, which is the major factor responsible for base scouring. Moreover, in comparison in physical modelling, either Reynolds or Froude similarity has to be ignored due to difficulties in meeting both similarity laws.

Therefore, perfect results are difficult to obtain in view of many factors involved that cannot be modelled directly using numerical simulation. The effect of the turbulent flow on the local scour around a single spur dyke was investigated by Zhang et al. [29]. They simulate the complex local flow field around the scour area using a three-dimentional nonlinear model that employs the finite volume method. They found that the simulation results are reasonably consistent with those of the experimental measurements. Down-flow, horse show vortex, and wake vortex are important parameters affecting the local scouring.

Bateni and Jeng [5] predicted scouring for group of piles using an adaptive neuro-fuzzy inference system model. The model used two combinations of input data to predict the scour depth: the first input combination involved dimensional parameters such as wave height, wave period, and water depth, while the second combination contained non-dimensional numbers including the Reynolds number, the Keulegan–Carpenter number, the Shields parameter, and the sediment number. The results show that the model better predicted the scour depth with the original dimensional rather than the non-dimensional numbers. The sensitivity analysis showed that the scour depth is governed mainly by the Keulegan–Carpeneter number, and wave height has a greater influence on scour depth than the other independent parameters. Lee et al. [17] applied the Back-Propagation Neural Network (BPN) to predict the scour depth in order to overcome the problem of exclusive and the nonlinear relationships. They verify the observations obtained from thirteen US states and found that the scour depth could be efficiently predicted using the BPN compared with conventional methods.

The present research fills the gap of literature, where there is limited experimental research on the effect of scouring on the structural behaviour of the integral bridges. Moreover, the present study also explores the simulation effect of flow velocities.

## Experimental work

The flow velocities effects on the structural behaviour of skewed integral bridge were determined from nine tests (three for three velocities; followed by six repeated tests) performed in the re-circulating flume at the Hydraulic Laboratory of the University of Malaya. The flume was 16 m long, 0.6 m wide and 0.57 m high. The model was tested in trapezoidal floodplains of 0.6 m wide, 2 m long, and 0.184 m high. Three parts of both side walls had clear Perspex panels, which are useful for clear and direct observation of the flow, scouring, and sediment transport process. A re-circulating pipe system was used: a centrifugal pump raised the water from a sump to the upstream end of the flume, from which it went back to the sump through a return pipe. The discharge was measured using a v-notch weir in the tank placed at the outlet of the flow. The bed sills/ floodplains used in all experiments were 142.2 mmthick by 18.4 cm high Perspex plates. The two floodplains were located at the longitudinal abscissa (starting from the inlet) x = 4.00 mand x = 6.00 m; the distance between the floodplains, L, was constantly equal to 2.00 m. The floodplains were used to observe the scouring and eroded sediments.

The riverbed material selected was uniform fine sand with a median particle size of $d_{50}$ = 0.13 mm in diameter. The sands were sieved in the range of 2 mm to 63 lm in order to obtain a uniform size for the bed sediment and according to British Standard 1377: Part 2: 1975. The sand that was trapped between these series of sieves had a range of 2 mm, 1.8 mm, 600 mm, 425 mm, 300 lm, 212 lm, 150 lm, and 63 lm. In addition, the specific gravity for the sand particles was determined for each type of sand. The sand diameter was chosen approximate to the average scale of all types of soils at the field site. This type of sand did not represent all types of soils for the actual rock and gravel in the case of the prototype structure, since it is impossible to scale down from the real soil conditions at the site.

Flow shallowness y was fixed at 1.5 cm and constant to serve as a control after being scaled down from the real water level in the actual flood. All runs used a skewed integral bridge model built on a deck fixed into an abutment, which was supported by a set of piles on both sides. Each side contained seven circular piles embedded at the base of the flood channel and fixed into holes 1 cm in depth at the bottom of the flow channel. There was a tolerance of 1 mm in the diameter that was filled with high strength adhesive material to model the fixed support conditions and to prevent transitional and rotational displacement in three dimensions.

The dimensions of each part of the bridge are shown in Table 1, and the scaling quantities are shown in Table 2. The model was made using perspex material having a density ranging from 1144 to 1250 kg/m$^3$, a modulus of elasticity of 2050–2300 kN/m$^2$, and Poisson's ratio of 0.39. The model was set up in the flood plain as shown in Fig. 1. Fig. 2 shows the plan view and the skew angle of the model. The skew angle is 34_ against the centre line of the flood channel. According to British Standards BS 4296, the maximum skew angle for integral bridge should be 30_; a skew angle greater than this precludes the use of integral bridge construction. However, a survey of recent practices revealed that designers are creating fully integral bridges with skews up to or slightly above this value. Yannotti et al. [28] reported that the maximum skew angle of integral bridge is 45_. Therefore, the skew angle for this study, 34_, is allowable and safe to be designed. Moreover, the velocities effects on the structural behaviour of skewed integral bridge would not be similar if the angles were different due to the different angle of attack on the water.

Each side of the piles was embedded into the flood plain. The elevation of the model is presented in Fig. 3, which shows the depth of the bridge model and the bridge dimensions as perpendicular to the flow flume. Sand was poured into the flood plain until half of the abutment was covered. The channel was also filled 5 cm high with sand. The water level was set to submerge the bridge's slab by 5–12 mm for all experiments in order to reach the effect of high water flow pressure on the bridge model and to be sure that all bridge parts came under the effect of water pressure.

Since the stabilization of the water level and the velocity were important in this experiment, several pre-experimental works were conducted to ensure a specific velocity upstream, and precise water levels were achieved before beginning each experiment. The velocities chosen in this study were referred to the frequent real-life flooding at Sg. Lebir, which is situated at Tualang, Kelantan. The flood velocity was 2.165 m/s (0.25 m/s after scaled down). The velocities chosen include slower than flooding (0.19 m/s), flooding (0.25 m/s), and higher than flooding (0.31 m/s). For all experiments, local scour depths were developed from flat bed conditions (ds = 0 for t = 0), with scour depths measured using a vertical scale depth positioned at all piles. The pile diameters were 8 mm to simulate the actual bridge with the dimension scale of 1:75, which was chosen according to the flume's limitation.

During the experiment, changes in scour depth on both sides of the abutment and piles were recorded. The experiment was repeated three times with three different velocities (0.19 m/s, 0.25 m/s, and 0.31 m/s). For each velocity, the experiment was repeated three times, and the average values were taken. The effect of these three different velocities on the scour depth was recorded. For the first 100 min of water flow, the scour readings were taken at 10-min intervals. Subsequent readings were recorded at intervals of 100 min for a continuous duration of 8 h and 20 min (500 min). The final readings were taken after 24 h of running the experiment.

The set of piles on each side are named Q and P, where Q is the set of piles located upstream. Therefore, Q was the first to come in contact with the water flow and thus the first to be affected by it; P was downstream and the last to be affected by the water flow. The main data recorded, in addition to scour depth, were strain and displacement on the bridge slab and on the Q set of piles. The actual bridge setup during the test is shown in Fig. 4. For strain, we used an electric resistant strain gauge, which measures sensitivity in microns to any change in the strain. Strain gauges were coated with bituminous material to prevent water intrusion, which acted as a waterproof covering to the gauges. To measure displacement, we used the Linear Variable Displacement Transducer, which measures displacement in mm units and is sensitive up to 0.01 mm. Calibration was performed before starting the experiments. The strain gauges and LVDTs for recording the strain displacement on the bridge slab and Q piles were positioned as shown in Figs. 5 and 6.

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