Numerical modelling of concrete bearing strength for different heights of concrete blocks

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Abstract. Bearing strength of concrete is one of important design characteristics in transmit the bearing force in structural supports such as column corbel, bridge bearing system, concrete connection, anchorage in post-tension members and other types of structure supports. Concrete bearing strength is depending on ratio of unloaded-to-loaded area and compressive strength of concrete. However, the effect of concrete block height on bearing strength of concrete is not included. Hence, the effect of different heights on concrete bearing strength were investigated using numerical modelling. The three-dimensional finite element model (FEM) for nonlinear analysis of concrete bearing were developed and analyzed in ABAQUS/Explicit. The FE models were validated based on pre-existing experimental results. The confinement effect and structural ductility of concrete blocks with different heights were evaluated. The FE results indicate that the level of internal confinement and the structural ductility of concrete blocks were affected significantly as increasing of concrete block heights. The bearing force for the concrete block with 150mm high was significantly dropped to 55% as compare to control specimen of 50mm high.

1. Introduction
The evaluation of bearing strength characteristic is crucial especially when designing the concrete transfer members such as concrete footing. The concrete bearing behaviour is relying on the contact mechanism between the steel bearing plate and the concrete surface. The steel bearing plate widely used as load dispersing plate for load transfer and intermediate supports for beam corbel, bridge bearing system and concrete anchorage system. Failure of concrete bearing is not an option as stability of structure is critical at their support base. The concrete bearing strength for unreinforced concrete block is depending on the unloaded to loaded area ratio and concrete compressive strength as stated in the Australian standards AS5100.5 [1]. For unreinforced concrete support, the bearing stress at concrete surface shall be taken as minimum value of
where \( A_u \) is unloaded area, \( A_l \) is loaded area, \( f'_c \) is concrete compressive strength, \( \phi \) is 0.6 for bearing.

Based on the formula [1], the effect of concrete block height is clearly not considered in the concrete bearing strength prediction. Other standards [2] also has the similar scenario. Earlier studies on concrete bearing was focused on the effect of different strength of concrete grade and the different unloaded-to-loaded area ratios [3 - 8]. In industry practise, the height of concrete support was determined depending on their design purpose [9]. In spite of important parameter for the concrete height in concrete bearing strength, only limited fundamental studies was available in literature. In previous studies, the ratio of height to width for concrete specimen is close to 1. Hence, the finding of these research may not reflecting the structural performance for low or high ratio of shallow and slender concrete blocks respectively. This present research was undertaken to extend fundamental explanation on bearing strength of concrete due to change of concrete block heights.

2. Methodology
The advanced software widely used in civil engineering especially due to limited data obtained from experiment. It leads some of complex behaviour of structural member is not easily explained. In the present study, FEM were examined the effect of concrete block height on concrete bearing strength in ABAQUS/explicit. The FE analysis is based on the structural response of the concrete block subjected to bearing force when loaded by steel bearing plate on concrete surface.

The quarter scale of three-dimensional (3D) FE model was developed to optimise the computational time. The size of FE model was determined based on the Australian Standard AS5100.5 for the expected bearing force of 3500kN. The size of concrete block and steel bearing plate was designed for 400mm by 400mm and 300mm by 300mm respectively. Five different heights of concrete blocks have been investigated through series FE models. The range of 50mm to 150mm for selected heights of concrete blocks were selected as considered for typical heights of concrete bearing footing in industry practise.

For the material model, behaviour for concrete (50MPa) was based on the Concrete Damage Plasticity Model (CDPM) (refer Table 1). For the contact behaviour, “Surface-to-Surface” contact was selected to stimulate the contact interaction due to frictional force and hard surface between concrete block and steel bearing plate. The contact surface is based on master to slave surface as shown in Figure 1.

| Table 1. CDPM for concrete with compressive strength of 50MPa. |
|-----------------|-----------------|-----------------|-----------------|
| Stress (MPa)   | Crushing strain (x10^5) | Stress (MPa) | Cracking strain (x10^5) |
| 15.00          | 0                | 1.99           | 0                |
| 20.20          | 74.73            | 2.83           | 33.33            |
| 30.00          | 98.84            | 1.87           | 160.42           |
| 40.30          | 154.12           | 0.86           | 279.76           |
| 50.01          | 761.53           | 0.22           | 684.59           |
| 40.24          | 2557.55          | 0.06           | 1086.73          |
| 20.24          | 5675.43          |                |                  |
| 5.26           | 11733.11         |                |                  |
In mesh sensitivity studies, the FE model was discretized for different mesh sizes to determine optimize mesh size that minimize the computational time. The optimise mesh size was obtained at 5mm. For the boundary condition, the surface of concrete block at the base surface was restrained in vertical direction. Due to symmetric loading and geometrical, quarter size model was developed based on plane of symmetry as shown in Figure 2. For loading condition, the incremental displacement was applied up to bearing failure.

For model validation, concrete blocks for 101.6mm and 203.2mm in three different ratios of concrete-to-steel area ($A_c/A_s$) of 2, 4 and 6 are considered. The concrete block has constant surface dimensions of 203.2 $\times$ 203.2mm for all specimens. Table 2 shows a series pre-existing database based on the experimental work [10].

| $A_c/A_s$ | height, h (mm) | Confinement effect, $f_b/f_{cu}$ |
|-----------|----------------|-------------------------------|
| 2         | 203.2          | 1.27                          |
| 2         | 101.6          | 1.37                          |
| 4         | 203.2          | 1.63                          |
| 4         | 101.6          | 1.75                          |
| 6         | 203.2          | 1.92                          |
| 6         | 101.6          | 2.00                          |

Concrete Compressive strength, $f_{cu} = 55.5$ MPa
Table 3. Finite element.

| Specimen No. | Block height, h (mm) | Ultimate load, $F_{ult}$ (kN) | Bearing strength, $f_b = F_{ult} / A_s$ (MPa) | Confinement $f_b / f_{cu}$ |
|---------------|---------------------|--------------------------------|---------------------------------------------|---------------------------|
| Fe-1          | 2                   | 1260.00                        | 60.75                                       | 1.22                      |
| Fe-2          | 2                   | 1436.60                        | 70.56                                       | 1.41                      |
| Fe-3          | 4                   | 849.20                         | 82.27                                       | 1.65                      |
| Fe-4          | 4                   | 902.20                         | 87.42                                       | 1.75                      |
| Fe-5          | 6                   | 610.80                         | 88.54                                       | 1.77                      |
| Fe-6          | 6                   | 746.80                         | 108.25                                      | 2.16                      |

Concrete Compressive strength, $f_{cu} = 50$ MPa

The accuracy of FE results in predicting of confinement effect of concrete have been evaluated by comparing with the experimental results [10]. In the present study, the confinement effect is referring to the ratio of bearing stress at the concrete surface ($f_b$) to compressive strength of concrete ($f_{cu}$). Table 3 shows the results of FE models for different ratio of 2, 4 and 6 for steel bearing plate size 144.02mm $\times$ 144.02mm, 101.6mm $\times$ 101.6mm and 83.06mm $\times$ 83.06mm respectively. Note the constant concrete surface of 203.2mm $\times$ 203.2mm was used in all FE models.

There is a significant different of compressive strength between experiment (55MPa) and modelling (50MPa). Hence, the results have been normalized by applying two important dimensionless parameters:

a) The confinement effect is the ratio of bearing pressure divided by compressive strength of concrete ($f_b / f_{cu}$)

b) The ratio of concrete surface divided by surface area of steel plate ($A_c / A_s$)

It can be seen Table 2 and 3 that the confinement effect ($f_b / f_{cu}$) for both experimental and FE results are consistence.

Figure 3. FE and experimental [10] for height concrete block of 101.6mm.
Figure 3 and 4 show the significant results on the trends of confinement effects for different bearing ratios \((A_c/A_s)\) in different heights of concrete block under bearing load. It proved that FE models able to capture the reasonable trend of confinement effect due to contact interaction between steel bearing plates for different height of concrete blocks. It was found that the trend remained the consistent irrespective of height of concrete blocks. The prediction of confinement effect of concrete \((f_c/f_{cm})\) under bearing force was in good agreement with previous experimental results [10] for all different ratios of \((A_c/A_s)\).

3. Results and discussion
Series FE models were evaluated based on control model of 50mm high and further examine for different height of concrete blocks, i.e. 75, 100, 125 and 150mm. In the present study, the structural performance of concrete blocks under bearing load was evaluated based on their ultimate load and structural ductility. The ductility was calculated based on maximum displacement divided by displacement at yielding. The results of FE models for load-displacement relationship are shown in Figure 5.
Figure 5. Load-displacement relationships for all FE models.

Figure 5 shows that the ultimate load of control specimen significantly dropped from 3668.50kN to 1667.50kN when the concrete block has increased their height from 50 mm to 150 mm. It was notified that the concrete block with 150mm height has reached the ultimate load was delayed at displacement of 0.214mm as compared to control specimen at displacement of 0.114mm. It was proved that changing of the height of concrete block have significant effect on the bearing strength and ductility of concrete block under bearing force. These results were further analysed in Table 4 and 5.
Table 4. Structural performance of concrete blocks under bearing force.

| Height  | Displacement at max. load (mm) | Ultimate load (kN) | Percentage reduced (%) | Vertical stress at the sharp edge (MPa) |
|---------|-------------------------------|--------------------|------------------------|----------------------------------------|
| 50mm (Control) | 0.114                         | 3668.50            | -                      | 37.66                                   |
| 75mm    | 0.132                         | 2866.91            | 22                     | 33.51                                   |
| 100mm   | 0.157                         | 2343.69            | 36                     | 28.86                                   |
| 125mm   | 0.184                         | 2002.49            | 45                     | 27.46                                   |
| 150mm   | 0.214                         | 1667.50            | 55                     | 25.59                                   |

Table 5. Structural ductility for all models.

| Height  | Displacement at yield point (mm) | Max. displacement (mm) | Ductility | Stiffness at yield point (x10^6Nmm⁻¹) |
|---------|----------------------------------|------------------------|-----------|--------------------------------------|
| 50mm (Control) | 0.064                           | 0.131                  | 2.04      | 43750                                 |
| 75mm    | 0.078                           | 0.157                  | 2.01      | 27215                                 |
| 100mm   | 0.080                           | 0.184                  | 2.30      | 21975                                 |
| 125mm   | 0.090                           | 0.214                  | 2.37      | 16683                                 |
| 150mm   | 0.095                           | 0.277                  | 2.92      | 13888                                 |

Table 4 shows that the ultimate load for concrete block with 150mm height was reduced up to 55% as compared control specimen (50mm). It was noted that the highest vertical stress at the sharp edge is 37.66MPa for control specimen due to highest contact area. For height of concrete block 150mm, the vertical stress is significantly dropped to 25.59MPa.

Table 5 indicates that increase of the block height has highest ductility due to high penetration of small steel bearing plate on the concrete surface. However, in term of stiffness, the height of concrete block 150mm was lowest which explaining the slender concrete block has lower bearing force capacity as compared to shallow concrete block. It indicates that at the high displacement, the shallow concrete block can resist higher bearing force as compared slender concrete block. In design stage, perhaps more precaution is needed especially when dealing with slender concrete blocks.

4. Conclusions
The FE models have examined the structural responses of concrete bearing for different heights of concrete blocks. The following observations are made based on data generated from the predicted results:

1. The height of concrete block is an important design parameter in determining the bearing capacity of concrete blocks. However, none of existing standard or design equation in previous national standards has taken account this parameter. It was observed that the increasing of concrete block height has significantly reduced the load bearing capacity of concrete.

2. It was noted that the ultimate load for the concrete block with 150mm high was dropped up to 55% of control specimen for 50mm high. The increase of height of concrete block has improved the ductility of the structure but the stiffness is significantly reduced which explaining the slender concrete block has low bearing force capacity as compared to shallow concrete block.
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References
[1] AS5100.5 2004. Australia Standard for Concrete Structures, Standards Australia Limited.
[2] ACI Committee 318, Building Code Requirements For Structural Concrete (ACI 318-99) and Commentary (318R-99), America Concrete Institute, Farmington Hills, Mich., 1999, pp. 391.
[3] Roberts-Wolimann, C. L., Banta, T., Bonetti, R. & Charney, F. 2006. Bearing strength of lightweight concrete. ACI Materials Journal, 103(6), pp. 459.
[4] Zhou, W., Hu, H. & Zheng, W. 2013. Bearing capacity of reactive powder concrete reinforced by steel fibers. Construction and Building Materials, 48, pp.1179-1186.
[5] Bonetti, R., Roberts-Wollmann C. L., & Santos, J. T. 2014. Bearing Strength of Confined Concrete. ACI Structural Journal, 111(6), pp. 1317.
[6] Yahya, N. A., & Dhanasekar, M. 2014, Explicit finite element modelling of bridge girder bearing pedestals in The 23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23), Dec 9-12, Southern Cross University, Byron Bay, Australia.
[7] Md Zain, M. R., & Yahya, N. A. 2017, Pertanika Journal of Science and Technology, 25(S), 67-76.
[8] Scheffers, C. A., Sri Ravindrarajah, R., & Reinaldy, R. 2011. Bearing Strength of CFRP Confined Concrete. Paper presented at the Advances in FRP Composites in Civil Engineering: Proceedings of the 5th International Conference on FRP Composites in Civil Engineering (CICE 2010), Sep 27–29, 2010, Beijing, China.
[9] Yahya, N. A., & Dhanasekar, M. 2017, Strategies for mitigation of the failure of concrete pedestals supporting bridge girder bearings, PhD Thesis, University Technology of Queensland.
[10] Au, T., & Baird, D. L. 1960. Bearing capacity of concrete blocks. Journal of the America Concrete Institute, 56(3), pp. 869-880.