Behaviour of residential structures on problematic ground

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Abstract. Different types of structures behave differently on the effect of differential settlement. In this study, 40 buildings were selected to represent the vast development of national houses. The buildings were selected based on visual observation on cracks and tilted walls. The buildings comprise mostly of piled and unpiled raft foundation supporting framed structures and shear wall structures, except one framed structure with isolated piled foundation. Performance of the structures was compared by using angular distortion. It has been proven that angular distortion can give an indication of the order of magnitude of stresses induced by deformation of the ground. Shear wall structures were found to be more sensitive to vertical ground movement compared to framed structures.

1. Introduction

The response of a building to settlement is dependent on the bearing capacity of the ground and the type and loading condition of the structure. Differential settlement occurred when a structure moves unevenly due to uneven movement of ground. By definition, differential settlement is the differences in vertical displacement of foundations. Uneven settlement at support may result in significant loss of load carrying capacity and thus resulting in damages to various parts of the structure. The ground movement profile is dependent on the soil parameters supporting the foundation and the load applied from the building. The said profile could be concave, convex or the building tilted on one side.

Differential settlement is a common cause of cracks in buildings and it may result in abandonment of the building, depending on the severity of the damages. The remedial actions are usually difficult and require careful analysis of the ground movement. Correct diagnosis of such a problem will avoid unnecessary spending on inappropriate remedial measures.

Differential settlement can cause a structure to rotate or distort causing large strains within structural element and thus a high potential of damages depending on the difference in magnitude of settlement between two points under a structure and the various aspects of the foundation and structural design. The degree of damages can be range from architectural damages such as sticking doors and windows, cracks in wall panels, tiles and plaster, uneven floors to severe cracks in structural elements which could affect serviceability of the structure.

2. Diagnosing differential settlement cracks

Any damages on architectural elements, particularly on infill masonry panels, can usually give a good indication of initiation of differential settlement, then damages to structural elements follows. However, it is always necessary to first verify the causes of crack whether it is due to foundation
settlement, shrinkage and incompatibility of materials, chemical reactions, thermal movement or the design. It is essential to investigate all possibilities of the causes of the cracks, and finally consider if the crack is a cause of ground movement after having ruled out the others.

In principle, buildings constructed of concrete and bricks are weak in tension. The tension within the material is caused by elongation. When one side of brick panel settles, the distortional effect causes the diagonal of the panel at the settled support to be lengthened and stretched. The resultant tension force pulls the panel apart causing the material to crack. Thus, the crack would be at right angle to the direction of tension. This is the first step to be done to identify damages due to differential settlement. Generally, diagonal cracks extending from openings edges within brick panel can be commonly observed due to presence of structural weak links at the edges of the openings.

The cracks due to differential settlement are likely to initiate at corner of door and window openings or weak structural connections, and it may initiate at higher level of the structure because tendency of horizontal displacement is higher at top level. Cracks in wall panel are usually diagonal, with the horizontal crack measurement normally wider than vertical [1]. This is because the associated rotational movement of structure from differential settlement makes the cracks wider horizontally and the gravity tends to close up the vertical displacement.

3. Angular distortion in structures
The allowable settlement is defined as the acceptable magnitude of settlement that will not affect serviceability of a structure. The determination of tolerance to ground movement by using angular distortion has been proven to be effective by other researchers.

Differential settlement between supports causes distortion and distress to that particular section of the structure. A differential settlement of 50 mm over a span of 4 m may result in greater damage compared to longer span experiencing the similar differential settlement magnitude. This is because the resulted distress is greater in the shorter span.

Angular distortion is the ratio of differential settlement between two points and the horizontal distance apart, less the tilt. Ground settlement under a building is not necessarily a straight line. Hogging or sagging curvature generally exists in related to settlement. Boone used the concept of defining vertical curve in surveying to determine the deflection angle of ground profile [2]. A load bearing wall with symmetrical hogging ground movement profile is illustrated in Figure 1.

Figure 1. Geometry and notation for deformation of load bearing wall due to settlement (after Boone).

The angular distortion between two points:

$$\beta = V_1 = \theta_1 + \delta/L$$ (1)

The radius of curvature is large enough that the angle \(\theta_1\) between the tangent and the chord is significantly small, therefore

$$\beta = \delta/L$$ (2)
The relationship is applied to the series of level readings taken around compound of the representative structures to provide an indication of pattern of vertical movement at the part of structure support.

Skempton and MacDonald [3] concluded in their study on response of conventional frame structures and masonry load bearing walls founded on sand or clay that an angular distortion limit of 1/150 for structural damages, 1/300 for cracking in wall panels and with a factor of 1.5, a limit of about 1/500 was suggested as the allowable value to avoid differential settlement damage.

Polsin and Tokar [4] adopted quite similar approach using ‘slope’ and ‘relative deflection’ between two adjacent supports. Their findings agree with Skepmton and MacDonald’s [3] on framed structures, taking additional accounts on structural stiffness on Length to Height ratio and the type of building. The proposed limits were 1/200 for structural damage and 1/500 for wall panel. Day [5] studied on behavior of timber framed structure and the proposed limits are 1/100 and 1/300 for structural and wall panel damage limits. March and Thoeny [6] did a study specifically on damages of slab-on-grade foundation of timber framed structures and concluded a proposed limit of 1/230 before the structures experiencing low levels of damage due to settlement.

Table 1 summarized the proposed limits from literature review above. The damaging limits for wall panels were found quite consistent across reinforced concrete, steel and timber framed structures. However, damaging limits to structural elements within timber structures was found comparatively higher as compared to reinforced concrete and steel frame structures due to flexibility of its structural connections.

| Type of Damage | Reinforced Concrete & Steel Frame | Timber Frame |
|----------------|----------------------------------|--------------|
|                | Skempton & MacDonald             | Polsin & Tokar | Day   | Marsh & Thoeny |
| Structural     | 1/150                            | 1/200         | 1/100 | 1/230          |
| Wall panel     | 1/300                            | 1/500         | 1/300 | -              |

Different type of structures can behave differently on the effect of differential settlement based on the type of design, construction method, type of foundation and capacity of soil underneath it. This paper is intended to explore the tolerable limits of shear wall structures built on problematic soil such as peat, using angular distortion as the key parameter and compare response of such structure to ground movement against framed structures.

4. The scope of study
The scope of this research is to study the difference between the behaviors of framed structure and shear wall dominant structure under the effect of differential settlement. The research is aimed to explore the sensitivity of framed and shear wall structures to differential settlement through field data collection work from the existing low-cost national development houses.

Based on the preliminary survey conducted, 5 sites from the low cost national housing development in Brunei were selected for the study to investigate the performance of shear wall structures and framed structures [7]. A total of 40 buildings were selected as representative houses to produce qualitative data of the structures in response to differential settlement. The 40 representative buildings selected from the 5 sites as shown in Table 3.2, based on observed cracks and visually tilted walls.

4.1. Site 1
The framed structure houses were built on sand replaced peat ground and founded on 200 mm thick waffle raft with primary beams of 750 mm depth and secondary beams of 600 mm depth, with end
bearing piles. Identical damages were observed at front and rear brick panel walls with some of the cracks penetrated through the walls (see Figure 2).

4.2. Site 2
Similar to Site 1, this site is situated on sand replaced peat ground. The peat up to depth ranging from 4 m to 6 m was removed and backfilled with sand by hydraulic method to its designed platform level which is 1 m to 1.5 m higher than the original ground level. The self-compacted sand thickness ranged from 4.7 m to 5.3 m and designed with minimum SPT of 15 to provide sufficient bearing capacity for the thick raft foundation.

| Site | Type of house | Type of structure                  | No of house |
|------|---------------|-----------------------------------|-------------|
| 1    | Terrace 8 units | Framed structure / piled raft     | 3           |
|      | Terrace 6 units | Framed structure/ piled raft      | 4           |
| 2    | Semi detached  | Shear wall structure / unpiled raft | 20          |
| 3    | Terrace 6 units | Shear wall structure / unpiled raft | 9           |
|      | Semi detached  | Shear wall structure / unpiled raft | 2           |
| 4    | Terrace 6 units | Shear wall structure / piled raft | 1           |
| 5    | Detached       | Framed structure / piled foundation | 1           |
| Total|               |                                   | 40          |

Figure 2. Cracks observed from site 1 structure (a) Front brick panel, and (b) Rear brick panel.

The semi-detached structures are designed using the concept of tunnel formwork with 100 mm thick shear walls as the dominant structural elements, with transverse beams on first floor and roof level as a tie to the walls.

The buildings are founded on raft of thickness ranging from 150 mm to 300 mm. The 150 mm thickness raft slab is for exterior apron and car porch, 250 mm generally on the main structure and 300mm thick to incorporate punching shear exerted from concrete shear wall. The raft slab is reinforced with two layers of BRC wire mesh. Similarly, the shear walls are reinforced with one layer of BRC wire mesh placed in the middle of the walls. A T10 bar is added at wall edge to act as anchorage reinforcement. The shear walls were casted in situ monolithically with first floor slabs.

The structures do not demonstrate much architectural damages. The brick panels were well confined between shear walls and lateral beams and no evidence of cracks or distortions around the openings. Identical concrete wall cracks initiated around the roof beam connections at concrete gable
walls were commonly observed, with some of it in severe condition (see Figure 3). In addition to that, some of the buildings can be seen tilted.

![Figure 3](image)

**Figure 3.** Cracks observed from site 2 structure (a) Front edge of concrete gable wall, and (b) Rear edge of concrete gable wall.

### 4.3 Site 3
The site is situated on a cut-and-fill ground. The structure is dominated by precast shear walls with 150 mm thick main exterior walls and 135 mm thick for internal walls. The 150mm thick walls are reinforced with two layers of BRC and two T10 bars added to the wall edge whereas the 135mm thick walls with one layer of BRC placed in the middle of the wall and a T10 bar at the edge. All walls are spliced with equally spaced T15 bars from in-situ structure. The structures are founded generally on 250mm thick raft with 300mm thick at the wall locations. The terrace houses were built using semi-modular structures on cut and fill ground. Massive cracks were observed on concrete walls, slabs and brick panels (see Figure 4).

![Figure 4](image)

**Figure 4.** Cracks observed from site 3 structure (a) Brick panel, (b) Slab, and (c) Concrete wall.

### 4.4 Site 4
The site is located on a peaty ground treated with prefabricated vertical drains. The selected structure is situated next to approximately 4 m high slope. The foundation design and general layout of the structural elements are generally similar to the structure described in site 1 but adopted shear walls as the dominant structural element. Thickness of the walls is 150 mm. Similar damages as site 1 were observed at rear brick panels of the building (see Figure 5).

### 4.5 Site 5
This conventional framed structure is a detached residential building located at untreated peaty ground and founded on isolated piles. Severe damage of 15mm crack width and 130mm depth were observed extended from column at the main entrance to ground floor slab (see Figure 6).
5. Data Collection Methodology

The research commenced with on-site field data collection by taking reduced levels around perimeter of selected buildings with assistance of professional surveyor. The observed damages were documented in terms of building, location, nature of the damages and photographed. A number of houses at Site 1, 2 and 3 were observed with enormous defects. Readings of reduced levels of all around perimeter of the selected houses and measurement of tilt of walls were collected. Terzaghi [8] suggested that readings of at least 15 points of a defected building shall be referred to describe amount of ground movement. In this research, it was decided to take reduced levels from at least 16 points. The points were selected consistently at support points like columns and walls around exterior perimeter of similar buildings. Additional readings were taken as and where required depending on location of defects and obstructing features. The designed structural layout of the houses at Site 1, 2, 3 and 4 were quite similar (Figure 7). Each unit of houses consist 2 bays at the front, 3 bays at the rear and 3 bays on the side. The bay spans ranging from 3.4 to 5 m.

6. Data Collection Results

Table 3 represents the summarized data obtained from the representative buildings.

6.1. Relationship between maximum angular distortion, \( \delta/L \) and maximum differential settlement, \( \Delta \)

The maximum angular distortion \( \delta/L \) and maximum differential settlement \( \Delta \) shown in Table 3 was plotted to investigate the relationship following the method of Skempton and MacDonald, and Day. The graph in Figure 8 shows the resulted relationship for framed and shear wall structures on raft foundation.
Table 3. Summary of data.

| Site | Block | Building Type<sup>a</sup> | Type of Structure<sup>b</sup> | Max differential settlement Δ(mm) | Max angular distortion δ/L (arch) | Max angular distortion δ/L (struc) | Pattern of settlement profile |
|------|-------|--------------------------|-----------------------------|----------------------------------|----------------------------------|----------------------------------|-------------------------------|
| 1    | C10   | T8                       | FRP                         | 29                               | 1/364                            | sagging                          |                                |
| 1    | C11   | T6                       | FRP                         | 23                               | 1/494                            | sagging                          |                                |
| 1    | C12   | T8                       | FRP                         | 55                               | 1/312                            | hogging                          |                                |
| 1    | C23   | T8                       | FRP                         | 22                               | 1/405                            | sagging                          |                                |
| 1    | C26   | T6                       | FRP                         | 40                               | 1/364                            | hogging                          |                                |
| 1    | C25   | T6                       | FRP                         | 42                               | 1/564                            | sagging                          |                                |
| 1    | C24   | T6                       | FRP                         | 36                               | 1/425                            | hogging                          |                                |
| 2    | B1    | SD                       | SR                          | 30                               | 1/142                            | hogging                          |                                |
| 2    | B2    | SD                       | SR                          | 48                               | 1/89                             | hogging                          |                                |
| 2    | B3    | SD                       | SR                          | 13                               | 1/531                            | hogging                          |                                |
| 2    | B4    | SD                       | SR                          | 37                               | 1/84                             | hogging                          |                                |
| 2    | B5    | SD                       | SR                          | 11                               | 1/643                            | hogging                          |                                |
| 2    | B6    | SD                       | SR                          | 11                               | 1/650                            | hogging                          |                                |
| 2    | B7    | SD                       | SR                          | 24                               | 1/188                            | hogging                          |                                |
| 2    | B8    | SD                       | SR                          | 16                               | 1/531                            | sagging                          |                                |
| 2    | B9    | SD                       | SR                          | 15                               | 1/450                            | sagging                          |                                |
| 2    | B10   | SD                       | SR                          | 18                               | 1/544                            | hogging                          |                                |
| 3    | A1    | T6                       | SR                          | 18                               | 1/152                            | hogging                          |                                |
| 3    | A2    | T6                       | SR                          | 43                               | 1/256                            | hogging                          |                                |
| 3    | A3    | T6                       | SR                          | 73                               | 1/235                            | sagging                          |                                |
| 3    | A4    | T6                       | SR                          | 130                              | 1/32                             | sagging                          |                                |
| 3    | A5    | T6                       | SR                          | 95                               | 1/147                            | sagging                          |                                |
| 3    | A6    | T6                       | SR                          | 45                               | 1/333                            | sagging                          |                                |
| 3    | A7    | T6                       | SR                          | 60                               | 1/200                            | hogging                          |                                |
| 2    | BH3   | SD                       | SR                          | 13                               | 1/531                            | sagging                          |                                |
| 2    | BH2   | SD                       | SR                          | 11                               | 1/636                            | sagging                          |                                |
| 2    | BH4   | SD                       | SR                          | 26                               | 1/163                            | sagging                          |                                |
| 2    | BH1   | SD                       | SR                          | 10                               | 1/700                            | sagging                          |                                |
| 2    | BH5   | SD                       | SR                          | 11                               | 1/409                            | hogging                          |                                |
| 2    | BH6   | SD                       | SR                          | 14                               | 1/778                            | sagging                          |                                |
| 2    | BH7   | SD                       | SR                          | 34                               | 1/144                            | sagging                          |                                |
| 2    | BH8   | SD                       | SR                          | 43                               | 1/163                            | sagging                          |                                |
| 2    | BH9   | SD                       | SR                          | 27                               | 1/425                            | sagging                          |                                |
| 2    | BH10  | SD                       | SR                          | 13                               | 1/377                            | sagging                          |                                |
| 3    | AHS1  | SD                       | SR                          | 29                               | 1/513                            | hogging                          |                                |
| 3    | AHS2  | SD                       | SR                          | 27                               | 1/567                            | hogging                          |                                |
| 3    | AHT2  | T6                       | SR                          | 37                               | 1/567                            | hogging                          |                                |
| 3    | AHT1  | T6                       | SR                          | 40                               | 1/520                            | hogging                          |                                |
| 4    | DH1   | T6                       | SRP                         | 37                               | 1/450                            | sagging                          |                                |

<sup>a</sup> Type of building as follows: T8 - 8 unit terrace, T6 - 6 unit terrace, SD - semi-detached, and D - detached house.

<sup>b</sup> Type of structure and foundation as follows: FP - framed structure with isolated piled foundation, FRP - framed structure with piled raft, SR - shear wall structure with raft, and SRP - shear wall with piled raft.
The line of best fit for framed structures on raft foundation comprises of 7 blocks, shows relation of $\Delta/(\delta/L) = 10277$ in millimeters which is equivalent to 405 in inches. Comparing to the relationship established by Skempton and MacDonald (1956) of $\Delta/(\delta/L) = 350$ in inches (see Figure 9) which had been referred by Day (1990) and Marsh and Thoeny (1999), the result is comparatively lower. Skempton and MacDonald (1956) proposed $\delta/L = 1/300$ as the limit for cracking in brick panel. By substituting this value into the relationship $\Delta = 350(\delta/L)$, the limiting differential settlement for crack in brick wall likely to occur is 30mm. This limit corresponded to the data presented for site 5 where damage on brick wall was detected at differential settlement of 36mm and angular distortion of 1/158.

However, the relationship established by Skempton is not applicable in the case of framed structure on raft foundation. It is probably due to the effect of long raft. Using the relationship determined from Figure 8, and applying the $\delta/L$ value in the relationship with reference to the lowest value from block C5 of 1/564, the differential settlement limit $\Delta=10277/564 = 18$ mm for crack in brick wall to likely occur.

In the case of shear wall structures comprising of 32 blocks, the relationship is $\Delta/(\delta/L) = 3557$ in millimeters which is equivalent to $\Delta/(\delta/L) = 140$ in inches. It can be seen that shear wall structures is likely more sensitive to differential settlement compared to framed structures. From Table 3, taking the lowest value of $\delta/L = 1/778$ of Block BH6 from site 2 for wall panel crack to appear, the limiting value of $\Delta = 3557/778 = 5$ mm. Similarly, for structural crack limits, using the lowest value $1/409$, the limiting value of $\Delta = 3557/409 = 9$ mm. These limiting values agree with the data.

The reason why the shear wall structures are highly sensitive to differential settlement is likely due to the design of flexible raft slab, walls and first floor slab where brc wire mesh were used as the primary reinforcement.
Figure 9. Maximum differential settlement versus maximum angular distortion (a) Extracted from Skempton and MacDonald, 1956 and (b) Extracted from Day, 1990.

6.2. Comparison between cast-in-suit and precast shear wall structures
A comparison is made on effects of method of construction of shear wall using relationship of $\frac{\delta}{L}$ and $\Delta$ as shown in Figure 10. The gradient of line of best fit for both cases are quite close which is $\Delta = 3404(\frac{\delta}{L})$ for cast-in-situ structures and $\Delta = 3385(\frac{\delta}{L})$ for precast. It shows that the method of construction contributes less effect in the difference of severity of damages related to differential settlement.

6.3. Comparison on effects of length of building of shear wall structures
All the shear walls are two stories low rise structures and designed and constructed in the almost similar manner of structural details. The E/G of the buildings selected in this study is assumed to be
consistent for all buildings since similar concrete grades are specified for all buildings. Considering the difference in length between semi-detached and 6 units terrace buildings, the sensitivity of the buildings to differential settlement is investigated as shown in Figures 11 and 12, using the relationships of \( \Delta \delta / L \) against max \( \Delta \) and \( \delta / L \) against crack width, respectively.

The gradient of line of best fit \( \Delta / (\delta / L) \) in Figure 11 are 3404 and 3233 for semi-detached houses and terrace houses respectively. The 6 units terrace is having 3 times the length of semi-detached buildings. The result reveals that terrace buildings are only 5% more sensitive to differential settlement compared to semi-detached buildings. Both semi-detached (SD) and terrace structures (TS) had shown the same curve of best fit in Figure 12. It shows that the longer buildings do not show much difference in sensitivity to differential settlement compared to shorter building with the same height of shear wall structures.

**Figure 10.** Comparison on effects from method of construction of shear wall structures using relationship between maximum differential settlement and max angular distortion.

**Figure 11.** Comparison on effects of length of building of shear wall structures using relationship between maximum differential settlement and maximum angular distortion.
Figure 12. Comparison on effects of length of building of shear wall structures using relationship between angular distortion vs crack width.

7. Conclusion
The performance of framed structures and shear wall dominant structures on raft foundations under influence of differential settlement was examined under this study. Most of the structures are founded on raft, except one framed structure on isolated piles. The studies were made based on evidence of damages during field surveying works.

Proposed tolerable limits by other researchers cannot be simply referred to the structure with similar design concept. The ground condition and type of foundation are key factors to consider. The angular distortion limit for framed structure on peat is found far below the limits proposed by other researchers shown in Table 1.

The damages of unpiled raft structures appear to be inconsistent with respect to both hogging and sagging deflection. The data suggested a more sensitive relationship of $\Delta = 3557(\delta/L)$ in millimeters (equivalent to $\Delta = 140(\delta/L)$ in inches). This is probably because of the design concept that the raft slab and walls are using brc mesh wire as the primary reinforcement. The proposed tolerable angular distortion limits and the maximum differential settlement before cracking occurred are shown in Table 4.

The result of relationship for shear wall structure under cast-in-site and precast construction method was compared and found to be quite close which is $\Delta = 3404(\delta/L)$ for cast-in-situ structures and $\Delta = 3385(\delta/L)$ for precast. This reflects that methods of construction do not contribute much difference in effects of differential settlement.

The effects on L/H ratio on shear wall structures were also investigated and found that buildings which are 3 times longer with the same height only 5% more sensitive to the shorter buildings.
Table 4. Proposed tolerable angular distortion limit and maximum differential settlement.

| Type of structure and foundation | Architectural element | Structural element |
|----------------------------------|-----------------------|--------------------|
|                                  | Tolerable angular distortion limit | Maximum differential settlement (mm) | Tolerable angular distortion | Maximum differential settlement (mm) |
| Framed structure with piled raft | 1/560                  | 18                 | -                              | -                                  |
| Shear wall structure with unpiled raft | 1/780                  | 5                  | 1/140                           | 9                                  |

Acceptability of settlement of foundations should be determined uniquely for stability and integrity of a structure based on tolerable movement of their foundation and soil underneath. The relationship \( \Delta = 3557(\delta/L) \) is therefore proposed to set as a reference solely for shear wall structures with raft foundation with the concept of structural design for the buildings undertaken for this research.

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