ABSTRACT

This paper presents a case study of cracks and fractures in buildings in Lobatse in southeast Botswana on walls and floors of houses and on new roads. The worst cracking is on houses in Woodhall I and II townships built through the Self Help Housing Agency (SHHA) programme, but other areas in town are affected. The average crack or fracture width is 10 mm, while the mode is 6 mm with a maximum width of 64 mm. Cracks are oriented in two principal directions: NE-SW and NW-SE and large cracks trend NE-SW. The widths of the cracks were used to derive the severity and the rate of crack development because the severities of cracks ultimately affect the aesthetic appearance of the house, including its use and overall stability. All the visited homesteads in Woodhall I and II, more than 90% of them contained a cracked building, more than 85% of the cracks lengths were long; affecting the whole house and more than 20% of the cracks are classified as severe to very severe. Are the cracks caused by activities of far field stresses such as earthquakes, choice of building materials or is this a local phenomenon?

KEY WORDS

SHHA, rehabilitation, Cracks, Expansive soils, Maintenance, house aesthetics, severity, Botswana

1. Introduction

Recently, several construction projects in Botswana have developed cracks and fissures immediately after completion (Mapeo, 1994; Council for Geoscience, 1999). These fissures, cracks and fractures affect the built up structures in many ways and are an economic burden to local authorities and individual house owners. An understanding of how fractures develop and form in natural rocks, including patterns and characteristics and cause is important in trying to find remedial and mitigation programmes in building projects affected by fracture development. Knowledge about fracture development is gained from detailed analysis of fractures in the houses. The underlying rocks and soils in the zones of interest are also important elements that need consideration in describing how cracks form. Cracks form because of the settlement damage of the houses caused by poor drainage because of flooding and rainfall, leaks, trees, soils shrinkage due to prolonged drought conditions and incorrectly compacted soil fill during the construction of the houses. Neotectonic ground movements in the region or occasional blast activities during construction, and inadequate building supervision and building using poor quality materials are also factors in crack formation. The houses in Woodhall I and II, Maokaneng and Pitikwe were built largely through the Self Help Housing Agency (SHHA) established by the Botswana Government to assist the low and middle lower income households to have access to housing in urban areas. This programme has been largely successful in providing access to housing to the intended groups of people. This programme also had the added advantage that participating low income households were given land freely and allowed to develop their houses over time (Ikgopoleng and Cavrić, 2007). The downside to this was that there was inadequate provision of services, lack of supervision of construction by the Urban Councils, and thus the houses that were built were very poor as no building standards were followed or prescribed.

In this paper, we use the example of cracked houses in Woodhall I and II townships in Lobatse built on weathered mudstones of the Upper Transvaal Supergroup (Key, 1983; Carney et al., 1994; Key and Ayers, 1998; Mapeo et al., 2006) to understand how fractures develop including their effects on the buildings. We have used the guidelines of the Royal Institution of Chartered Surveyors of the United Kingdom (www.rics.org/uk) to appreciate the severity of the fractures in the houses. The Woodhall I and II houses are built on residual soils (~3-8 m thick) comprising moderately, to well drain sandy clays. The residual sands and alluvial clays cover a north-south strip of land on which some sections of Maokaneng, Woodhall I and II, and Pitikwe are also built (see Figure 1a,b) on rock units of the Upper Transvaal Supergroup. To the west of Woodhall II these mudstones are weathered and are used for the production of clay fired bricks (Key, 1983).
2. Theoretical Development of Fractures

The development of fractures is related in many ways to what geologist term brittle deformation, which occurs in the upper few kilometres of the continental crust. Brittle deformation structures are the dip-slip faults related to extension, thrust lip faults related to compression and strike-slip faults related to transform motions. Generally, normal faults dip on average 60°; thrust-slip faults dip on average 30°, and strike-slip faults are vertical (see Figure 2). To understand the faulting (fracture formation) we need to appreciate stress conditions and patterns under which rocks break to form fractures/faults.

The earth surface is always under constant stresses, made up weight exerted by soil, rock overburden and built-up structures. Stresses are made up three components ($\sigma_1$, $\sigma_2$, and $\sigma_3$) orthogonal to each other. The magnitudes of the principal stresses are indicated as $\sigma_1 > \sigma_2 > \sigma_3$. The contributions to stresses in built-up areas include the overburden material oriented vertically; so the other two stresses are oriented horizontally. The new fractures or cracks that form will always be at right angles to the minimum stress (Price and Cosgrove, 1990; Ramsay and Huber, 1990). In this respect, the direction along which a fracture develops is dictated by the relative magnitudes of the horizontal stresses and their orientations as illustrated in Figure 2a-c; and obeys the Coulomb law of failure and formation of brittle structures near the surface of the earth. If $\sigma_1$ and $\sigma_3$ are both oriented horizontally strike-slip conditions are favoured, when $\sigma_1$ and $\sigma_2$ are horizontal thrust-slip conditions develop and when $\sigma_1$ is vertical and $\sigma_2$ and $\sigma_3$ are horizontal dip-slip conditions are favoured.

In nature the development of fractures accompany other types of motions or inversely put can be caused by other types of Earth movements. The orientations of the principal stresses also dictate the formation of joint sets in rocks and building. There are three directions along which new fractures will open: (i) orthogonal to the plane of the crack (Mode I cracks); (ii) parallel to the plane of the crack and perpendicular to the crack front (Mode II cracks) and (iii) a scissor type motion acting parallel to the plane of the crack (Mode III cracks) (see Figure 2d). An additional complication in studying causes of fractures is that they can form because of movements on large-scale geologic structures such as faults or be associated with large Earth tremors (Price and Cosgrove, 1990). The understanding of crack formation requires an appreciation of the various types of cracks that develop and their orientation. Cracks in houses have many causes that include subsidence or foundation movements owing to changes in ground conditions below and around the house making the house to move slightly leading to cracks formation.
Figure 2: Schematic representations of (A) Normal faults, (B) Thrust faults, (c) Strike-slip faults, and (D) Three fundamental fracture modes: Mode I-opening perpendicular to the walls of the fracture surface; Mode II-sliding in the direction parallel to the fracture surface, parallel to the fracture front and Mode III-a scissor motion or tearing in the direction parallel to the fracture surface, perpendicular to the fracture front.

3. Research Problem
In this paper we focus on the mapping of cracks in houses in Woodhall I and II townships of Lobatse in Botswana and use fracture type, width and orientation to characterise the cracking in the houses. We use fracture orientations in older rocks as control and last, we performed temporal analysis of cracks in some houses to gain insight into the rate at which they develop. We inspected individual houses in Woodhall I and II for cracks in 2010 and 2011 as a follow-up of the study of Mapeo (1994). In this study, one hundred and thirty (138) homesteads were visited and fifteen (15) months later ten (10) houses were selected for inspection.

4. Results and Interpretations
4.1 Data analysis-types of Cracks
Three types of cracks were noticed in the walls and floors of houses in the Woodhall I and II townships:

(i) Horizontal cracks appearing along the mortar joints between brickwork and on the foundation. The cracks also occur above the damp proof plastic layer above the foundation.

(ii) Vertical cracks on internal and external walls connecting to cracks on the floor and on opposite walls.

(iii) Vertical cracks on roads, ground surfaces and on foundation slabs.

The cracks range in width from 1mm to 64 mm with an average of 10 mm and a mode of 6 mm wherein the largest widths ranging from 30 to 64 mm are in Plots 1924, 2511, 2515, 2516, 2518, 2521, 2532, 3182, 3222 and 3223. Plot 3182 is in a poor state of severe fracturing and has been abandoned because of this despite repeated attempts to repair the fractures. More than ninety per cent (>90%) homesteads visited contained a cracked building with most cracks found on floors; across the floor area from one end of the room to the other continuing into the walls.

The cracks when observed from outside the houses mostly affect the foundation to the roof level. The cracks are vertical and horizontal; occur on floors and walls with or with no signs of displacement. The window and door frames are not distorted and window panes do not exhibit any tension. Vertical cracks are the most common and extend to the lower edge of the foundation and constitute Mode I features without conjugate features (see Figure
Vertical cracks are elongated over long distances, and their lengths are unknown and unhelpful, but affect the whole house foundation; cumulatively they define a >10 km zone on top of the concealed Woodhall Fault. Most cracks have widths that range from less than 1 mm to 15 mm, and gradually decrease in frequency with increase in width size (see Figure 3).

The houses with extensive fractures are distributed over a wide area along north to northeast direction (see Figure 2b and 4). The wider cracks are few compared to the many narrow or small cracks. The smaller cracks include repeat cracking after the older crack region has been filled with new mortar. Cracks are oriented towards NE-SW and NW-SE (see Figure 4a, b) with variable displacements. The widths of cracks trending NE-SW are wider than of cracks of other orientations; suggesting continuous movement along the NE-SW direction allowing the growth of the NE-SW cracks.

In some houses, complex cracks form sub parallel cracks that join in anastomosing fashion to define special type of fractures known as Reidel-Shears (Price and Cosgrove, 1990). The presence of Reidel shears fractures or cracks suggest shearing movement (Mode III) in the area that may be related to a strike-slip motion of the ground along the SW-NE direction. The shearing movements cause vertical cracks in the foundation and in the walls above the damp-proof plastic layer. Another example of shearing is on outside toilet in Plot 3481 that shows walls of the toilet sheared in scissor type motion in a NW-SE direction suggesting cracks in houses have many causes (see Figure 5a) including but not limited to ground motions. The lateral displacements on the cracked houses range from 4 mm to 35 mm in width.

Unidirectional cracks were also identified in three houses in the in Plot 2339. The cracks form three major cracks...
that trend between at 233° and 240° with minor fractures branching from the primary NE trending fractures. The horizontal cracks are on the eastern side of the foundations, but do not, cut the full length of the foundation basement. Signalling that the foundation is failing under the weight of the surrounding soil and the building does not maintain the plumb and has bowed westward for example in Plot 4260.

The plumb of the buildings was not measured, however, as seen from Figure 5b, the cracks along the foundation in Plot 4260 has affected the plumb of this building. The lateral displacement inward (s) of walls is noticeable. The cracks have widths ranging from 12 mm to 35 mm showing the displacement of the upper part of the house (part overlying the foundation) inward (s) (see Figure 5b). The cracks observed outside the houses are unidirectional even when developed along points of weaknesses on walls show the same trend; the crack curves sharply along the mortar and again then vertically parallel to the same direction.

Figure 5 shows various photographs of cracks including cracks in Plot 2478 showing a sinuous crack on wall with the same general pattern and trend as the main cracks in the houses. A house in Plot 3182 has become inhabitable despite regular maintenance involving the filling of new and old cracks with plaster mortar; similarly Plot 3481 has also been abandoned whereas other plots have not been built up.

The economic burden to residents has not been computed but is associated with anxiety as to what can be done to alleviate the situation. A typical example is in Plot 3479; where the owners tried remedial measures to stabilize the house by patching cracks with mortar on wire mesh (see Figure 5c), as well as building concrete pillars hoping these will stabilise the house, however the cracks continue to form. More examples of fracturing are shown in Figure 5d-f.

The fractures induce problems on the structural integrity of houses as well as being an economic burden to house owners who have to meet costs related to rehabilitating houses for occupation. This is compounded by the fact that no guidelines are provided by the Town Council to home owners about a long lasting solution to the development of down cracks. Some plot owners have opted not to build houses in this zone.

4.2 Comparison of Crack and Joint Orientations

In the west of Woodhall I and II townships, near the High Court Building exposed are quartzite of the Black Reef Quartzite Formation nonconformably above the Quartzfeldspar Porphyry Rhyolite of the Lobatse Group (Key, 1983). The Black Reef Quartzite Formation forms a basal poorly sorted conglomerate with clast of rhyolite, overlain by a dark grey to light grey jointed quartzite with dips between 14 and 30 degrees towards the NE or SE reflecting the gently folding in the area.

Joints have variable dips that range from 54 to 88 degrees with north-easterly and south-easterly dips. Outcrops observations, show that some joints are complex and irregular compared with the typical extensional joints. Correlation exists between the fracture and crack in the houses and trends of joints in older lithologies. The joint fractures (faults) that coincide in trend with cracks in the houses are parallel to the strike of the geological units in the area. The brittle fracture zones in the older rocks are in filled by quartz veins that trend between NE and ENE and cut all the pre-Transvaal Supergroup rocks including the Lobatse Group (Key, 1983).

4.3 Building Methods

Most houses in Woodhall I and II with cracks are either built using block (450 mm x 230 mm x 115 mm) or concrete stock or face bricks (220 mm x 110 mm x 70 mm) and the depth to foundation is reported to be about 80 cm deep. The quality variations in erected buildings, in the methods and materials used in building (such as high and low-strength cement), the use of high to poor clay quality and cement bricks, poor mortar mix, and shallow to deep excavated foundations also plays a role in fracturing. The variations in these properties is apparent as cracks on houses built using block concrete bricks are bigger in width than those on concrete stock and on face bricks. The fact that buildings built using different brick-types are equally affected but differently by cracks suggests building methods and materials are not the primary cause of cracking.

Other causes of vertical cracks include settlement and compaction of the built structure, and or variation of soil moisture content. Mapeo (1994) showed cracks in some houses were caused by changes in the moisture content of clays along the NE trending Woodhall Fault Zone on which rows of cracked houses lie. Faults are zones of preferential groundwater drainage along which there is gouging of the shale by the continuous circulation of water leading to feldspar alternation into clay minerals such as montmorrillonite, chlorite, kaolinite, smectite and illite producing cohesive soils along the zone. Rainfall and groundwater water level records from boreholes at the Botswana Geological Survey yard for 1982-1993 varied between 18 and 22 m below the surface in the Woodhall area. The severe cracking is reported to occur during the rainy season owing to the swelling of clays and expansion of the soils. The second period of cracking is during the summer when soils are dry resulting in shrinkage of clays exerting pressure on the walls of houses and foundation that responds by cracking (Mapeo, 1994; Council for Geoscience, 1999).
The swelling and shrinking of the clays is followed by two processes:

(i) The clays soils below house foundations dry out allowing the foundation to drop.

(ii) During wet periods the clays swell and lift the house foundation.

The swelling and shrinking of the clays should normally not cause problems if the movement is uniform at every point along the foundation, however as seen in Woodhall I and II the movement is not equal as it comprises movement along the faults, swelling and shrinkage of clays soils that build stresses that cause cracks in the foundation and walls. The swelling, shrinkage of clays and movements along the Woodhall Fault Zone results in vertical fractures and horizontal fractures in the house foundations and walls.

4.4 Crack Development with Time

The widths of the cracks in the houses were used for calculating the rate of crack formation using
investigations made in June 2010 and again in September 2011. Widths of the crack recorded fifteen months apart, show increase with time (see Table 1). In addition, houses that had no cracks in 2010 had cracks in 2011 suggesting that the crack formation process was continuous.

Of the 138 homesteads visited, nine (9) did not have a cracked structure, which means that 93.5% of the homesteads in Woodhall contained a cracked building. There are examples of houses that exhibit extreme fracturing and have been abandoned (2011) because they inhabitable (Plot 3182 and) (see Figure 5). The pattern of cracked houses follows the same trend of elongation of Woodhall I and II townships that stretches from North East to South West (Figure 1).

<table>
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<th>House Number</th>
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<td>6</td>
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<tr>
<td>3607</td>
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</tbody>
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### 4.5 Crack Severity

The significance of cracks is described according to the Buildings Research Establishment (BRE) rules of the British Royal Institution of Chartered Surveyors standards. The severity of cracks is based on widths: cracks with widths lower than 5 mm are slight, and those with widths ranging from 5 mm to 15 mm are moderate and those that range from 15 mm to 25 mm are severe while those with widths greater than 25 mm are very severe. Severities of cracks in the houses are presented in Figure 6. Results show that of the 138 homesteads visited the majority are slight 79% and very severe cracks accounted for 10% in 2011. The proportion is an underestimate since cracking is a continuous process mitigated by filling the cracks with mortar.

Figure 6 shows that most cracks in houses have affected the aesthetic appearance of the houses (79%), but do not affect the functioning of the houses; however, there are houses (21%) with cracks that could affect the serviceability and stability of the houses. The latter types of cracks require attention. The development cracks seems to suggest the influence of ground movements likely to progress and inflict damage that range from aesthetic damage to damage affecting the serviceability and ultimately the stability of some houses in Woodhall I and II. The majority of fractures are vertical in nature and there for suggest either strike-slip movements (see Figure 2c) with both principal stresses in horizontal positions.

### 5. Discussion and Conclusion

The results of this study show that the distribution of cracks follows a general orientation along two principal directions of SW to NE and SE to NW. The cracks in the houses are parallel and perpendicular to the strikes of the Black Reef Quartzite Formation. The SW–NE trending cracks are parallel to this strike of the rock units and the SE-NW trending cracks trend perpendicular to strike of the same units. The correlations in fracture directions show that most cracked houses are distributed along the strike of the underlying rocks and widens with time forming another lineament of cracked houses.

Most houses have the same crack patterns of widths and orientation indicating that new cracks have followed the structural weaknesses in the underlying geology units on which the cracked houses are built. Open fractures in yards with no built structures trend in the same direction as most cracks in the houses, confirming the hypothesis that the fractures are oriented along the direction of older fractures such as faults and joints in the older rocks. The lateral displacements seen on some buildings imply that there is shearing movement during fracturing that affect the house on top of the foundation.

The fact that the houses continue to crack including newly constructed units built using new buildings methods (Lobatse Civic Centre) suggests that building methods are not the primary cause of cracks but contributory. Evidence showing houses continuing to crack along renovated zones suggests the process of cracking is continuous and will ultimately affect the serviceability and stability of the houses. The houses with cracks define a linear zone coincident with a buried fault defining a linear zone of weakness in the substratum enhanced and controlled by secondary soil properties because of
seasonal variations of moisture contents along the fault zone.

The lines of evidence suggest neotectonics may have a role in fracture and crack formation. Evidence for neotectonic activity is recorded by Late Pleistocene to Holocene earthquakes in the region (Andreoli et al., 1996). Faults of this age are shown by hot springs along fault zones in South Africa. In southeast Botswana, seismic events are related to deep mining in South Africa.

Deep mining activities alter the balance of forces in rocks by creating voids resulting in changes in the stress and strain regime. The changes causes rocks to burst and collapse producing seismic waves which may reactivate existing faults causing minor tremors and earthquakes. No large seismic events are recorded in this region of southeast Botswana, implying that movements seen as cracks in houses are related to the behaviour of expansive soil on which a section of the township is built.

![Figure 6: Pie chart showing the severity of the cracks on buildings](image)

**SEVERITY STANDARD:**
- Minor: less than 15 mm
- Severe: 15 mm-25 mm
- Very severe: over 25 mm

**6. Recommendations**

According to the authors to mitigate challenges related to cracking requires education on appropriate building standards informed by geotechnical surveys and thorough understanding of what the long term effects of cracks are to the aesthetics and stability of houses and the economic burden on the owners.

Residents of Woodhall I and II and other areas in Botswana need to be advised that:

i. It is possible to build safely near zones with expansive soils, provided stable moisture conditions are maintained around the house by insulating the building from soil moisture loss and gain.

ii. Design houses adhering to standards of building in expansive soils.

iii. The houses to be built after a detailed geotechnical survey which will delineate faults and appropriate safety zones.

iv. A zone in which building of houses is forbidden be demarcated along the area that is structurally unstable.

v. Define appropriate building codes for this region of southeast Botswana.

**Acknowledgements**

We are grateful for the financial support provided to RBM by the University of Botswana and by the Botswana Geological Survey to RBM and LL. DT acknowledges the scholarship award from the Ministry of Education and Skills Development. We also thank residents of Woodhall I and II in Lobatse for allowing us access to their homes during this study.

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