

Mapping Spontaneous Ground Fissures using Seismic Refraction, Reflection, and Ground Penetrating Radar in the Letlhakeng Area, Kweneng District, Botswana

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Abstract

Infrastructure in the Letlhakeng area is currently being damaged by ground fissures. Geophysical profiles of seismic refraction and reflection, and ground penetrating radar (GPR) were recorded at the areas affected by the ground fissures to map their depth extent and subsurface configuration. The GPR survey used 50 MHz antennas with an inline transmitter and receiver 2 m apart and a sample spacing of 30 cm. A reversed seismic refraction profile with two offset shots was recorded. Twenty four geophones were placed 2 m apart to make a total profile length of 46 m. The seismic reflection data were recorded with an equal source and receiver interval of 1 m and a total spread length of 23 m across a ground fissure. The GPR profile shows that the ground fissures are sub-vertical and extend to a vertical depth of ~5.0 m. The seismic refraction profile shows a two layer velocity model comprising overburden with a seismic velocity of 400-600 m/s lying over a substratum with a seismic velocity of 1200-1400 m/s. The top layer consists of the loose sand which is imaged to a depth of 5 m. The seismic reflection profile shows that the ground consists of sub-horizontal layers from 0-15 m depth, which have all been broken by the ground fissure observed at the surface. The geophysical results show that the ground fissures persist from the surface to depths of 15 m.

Keywords: Seismic refraction; Seismic reflection; Ground penetrating radar; Ground fissure; Seismic velocity

Introduction

There have been reports by residents of Letlhakeng, Ditshegwane, Metsebothoko, and Sesung Villages, in the Kweneng District, that infrastructure in the area is being damaged by periodic ground movement which gives rise to large ground fissures. These ground fissures are reported to cause damage to infrastructure like institutional buildings, private houses, and public roads. The ground fissures form during the dry seasons and prolonged droughts, and are closed by debris inflow during the wet seasons to become completely unrecognizable, only to develop again during the next dry season. Apart from causing damage to infrastructure, the fissures pose a geologic hazard to people and livestock since they are quite big and animals can fall into them. Although the ground fissures close in the wet season, the damage to infrastructure remains visible and it is the only evidence that there

is something wrong with the foundations of civil structures. The infrastructure damage is incremented in the next dry season until the structure fails completely, leading to closure and relocation of institutional buildings as it happened at the Mphu, the Junior Secondary School and the customary court building in Letlhakeng village [1]. The cause of this destructive ground movement is largely unknown but suspected to be related to either active seismicity or expanding clay underlying the buildings. The ground fissures vary in size from a few millimeters to several centimeters and even metres across. Along the paved Ditshegwane access road to the main Letlhakeng-Morwamosu highway, the ground fissures are oriented north-south and manifest themselves as small depressions and large ground fissures (Figure 1). The fissures appear to be a widespread phenomenon in the area as large ground fissures can be followed for tens of meters away from the paved roads. Local residents of Letlhakeng report the occurrence of large ground fissures at many places in the bush and within ploughed fields.

A number of geotechnical, geological, and geophysical investigations, Geotechnics International Botswana, Laletsang et al. [1,2] have been commissioned by the local authorities to establish the cause of the ground fissures damaging institutional property such as the schools, roads, and tribal administration buildings (Figure 2) and to suggest possible remediation measures that can be adopted. Most of these efforts were focused on the damaged structures themselves and did not consider the regional geological features which may have a bearing on the driving mechanism for the development of the fissures.



Figure 1: A large ground fissure developed on a sandy surface near Ditshegwane settlement. Note the global positioning system (GPS) device placed near the fissure for scaling. The fissure was open to a depth of ~2 m, measured by inserting a stick.

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Figure 2: A crack developed through the wall of the Letlhakeng customary court. This building has since been abandoned because of damage caused by the spontaneous ground fissures.

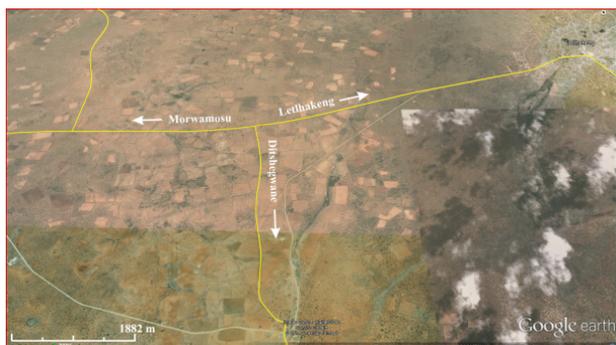


Figure 3: GoogleEarth™ image showing the location of Letlhakeng Village, the small settlements of Ditshegwane and Sesung, and the main paved highway through the area which has been severely damaged by ground fissures.

This paper presents the results of an investigation into the cause of the ground fissures in a regional geological context, using geophysical data acquired at different stages during localized seismic and ground penetrating radar surveys. The investigations are extended to cover the greater catchment area of the Letlhakeng Fossil Valley and its tributaries (Figure 3) with the aim to establish what role the stratigraphy and hydrogeological regime may play towards the development of the observed ground fissuring and damage to infrastructure. The findings of this investigation are intended to assist in the design and subsequent monitoring of civil structures erected on the soils underlying the Letlhakeng village, which is a development planning area.

Background

The seismicity of Southern Africa is discussed in Uzoegbo et al. [3] and shown in Figure 4. The seismicity recorded within the Republic of South Africa comprises mainly mining-induced earth tremors which are high frequency and of a shallow origin. Such seismicity poses a danger to single storey buildings since it is high frequency, but its energy is attenuated within 10 km from the source [3]. As such mine-induced seismicity is of concern only within the townships of the mining area.

High density earthquake seismicity is observed on the East African Rift System, which extends into Zimbabwe and northern Botswana. A good amount of both earthquake and reservoir-induced seismicity caused by the Kariba Dam is reported in western Zimbabwe along the Deka Fault which possibly extends into the Makgadikgadi Pans area of Botswana [4]. Similarly, the wall impounding of the Mahale Dam in Lesotho has led to a significant amount of seismicity [3]. The Mahale Dam wall-impounding seismicity is reported to have caused damage to property in settlements downstream of the dam. It can be seen in Figure 4 that the Letlhakeng area shows no previous record of seismicity, partially because of lack of coverage by the local seismic recording station network but also because no active faulting is known to occur in the area. Ground fissures are common in areas of active tectonics, volcanism, subsidence related to aquifer depletion, and mine-induced seismicity. In tectonically active areas, the ground fissures are a precursor to rock failure and are expected to occur. Geng et al. & Carpenter et al. [5,6] examined the distribution and development of ground fissures in mainland China and the USA respectively. Kenny et al. [7] gave an interesting perspective on the development and perceived causes of earth fissures in the USA, including an eye witness account of a developing earth fissure in Arizona. The ground fissures in southwestern USA such as Arizona and Utah can be large enough to be visible on Google Earth™ images [8,9]. Most studies in the USA conclude that the occurrence of a seismic ground fissures is induced by over-pumping of ground fluids leading to differential stress and eventually failure. In some cases, ground fissuring was observed to be related to monsoon flash flooding [5]. After concerted efforts aimed at mitigation of property destruction caused by seemingly a seismic ground fissure development in Riverside County, California, [10] concluded that the fissures were caused by hydro-consolidation and differential settlement related to rapid fluctuations of the groundwater table.

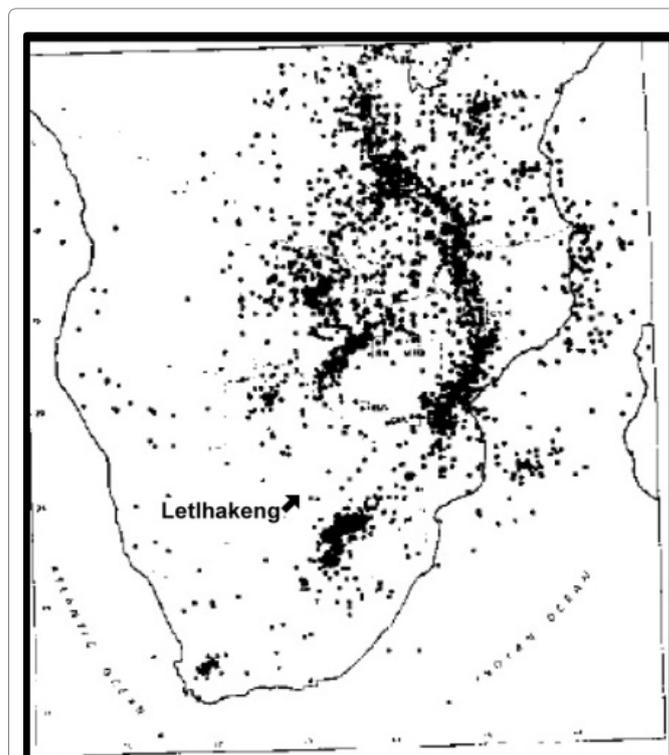


Figure 4: Distribution of active seismicity in southern Africa [3].

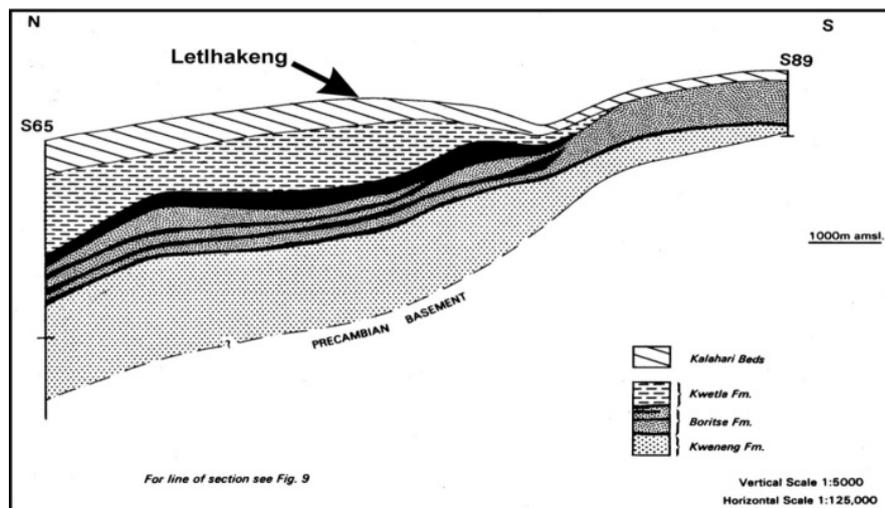


Figure 5: A N-S cross-section through the southeast Karoo sub-basin. The section shows formations of the Ecca Group resting un-conformably on Precambrian basement [11].

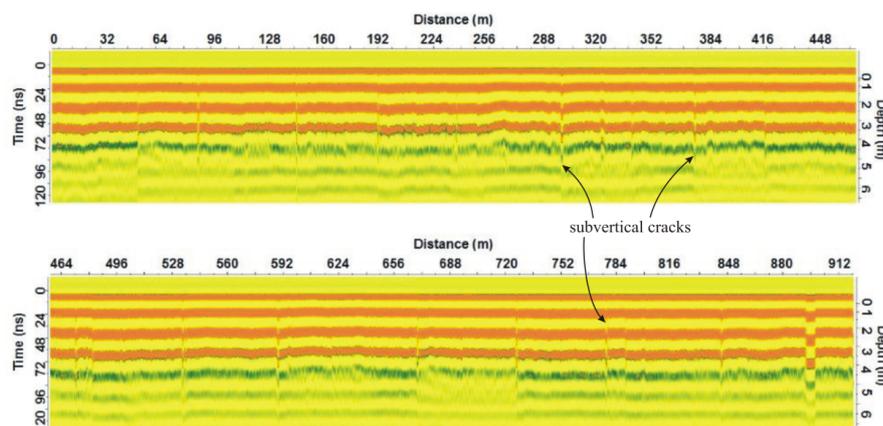


Figure 6: A ground penetrating radar profile recorded along a paved road near Ditshegwane settlement.

Physiographic setting

The Letlhakeng area comprises two physiographic terrains: a fossil valley incised deeply into a plateau of fine loose sand (Kalahari Group) which lie unconformably on weathered mudstones of the Lower Ecca Group of the Karoo Supergroup [11,12]. The Kalahari Group comprises unconsolidated deposits composed of mainly fine sand with some development of duricrusts within the fossil valleys [13]. Gwosz et al. [14] described a sub-economic occurrence of calcrete in the fossil valley to the east of Letlhakeng. The valley floor is underlain mostly by black cotton soil in addition to calcrete. The unconsolidated Kalahari sediments thicken to the west where they reach a thickness of up to 200 m. In the Letlhakeng area, the loose sand thickness reaches only up to 5-6 m while the calcrete may reach a thickness of 10-15 m.

The Karoo Supergroup comprises three Groups; namely Dwyka, Ecca, and Beaufort, deposited in an epicontinental basin under conditions varying from glacial to aeolian. The Karoo stratigraphic column is incomplete in Letlhakeng area because it occurs on the edge of the main Karoo basin (Figure 5). Here, the topmost unit of the Karoo Supergroup intercepted by water and exploration wells is the Lower

Ecca composed of mudstones underlain by an alternating sequence of carbonaceous siltstones [11,12].

Geophysical Investigations

Ground Penetrating Radar (GPR)

50 MHz unshielded antennae GPR survey was used to record a profile parallel to a paved road. The profile was recorded using an inline transmitter and receiver setup with a 2 m separation maintained with a wooden frame and recording at a sample spacing of 30 cm. The transmitter and receiver setup was maintained at a constant height of 5 cm above the ground surface and moved at a walking pace along the profile. Data recording was triggered with a hip chain running on a biodegradable cotton thread. The setup described here recorded a zero offset vertical profile which requires only a limited amount of processing besides signal editing and enhancement. Data editing, contrast enhancement, visualization and plotting was performed using Ground Vision™ 1.4.5 software. The GPR profile in Figure 6 shows that the fissures are sub-vertical and extend to a vertical depth of 4.5-5.0 m. The depth indicated here the electromagnetic signal weakens but the

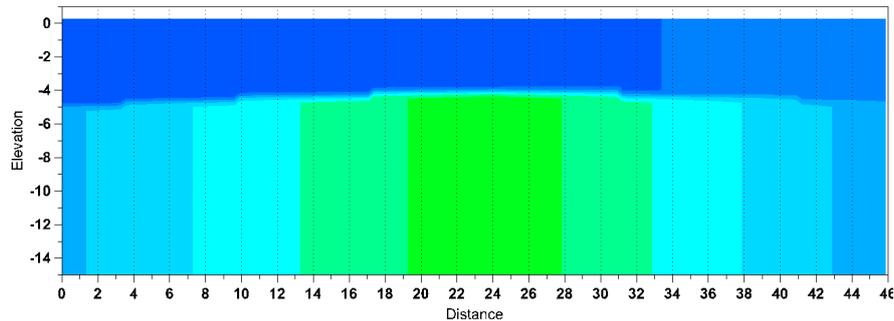


Figure 7: A seismic refraction profile recorded along the Ditshegwane road. The hairline cracks are not visible, but the top layer persists to 5 m, as indicated in the GPR profiles.

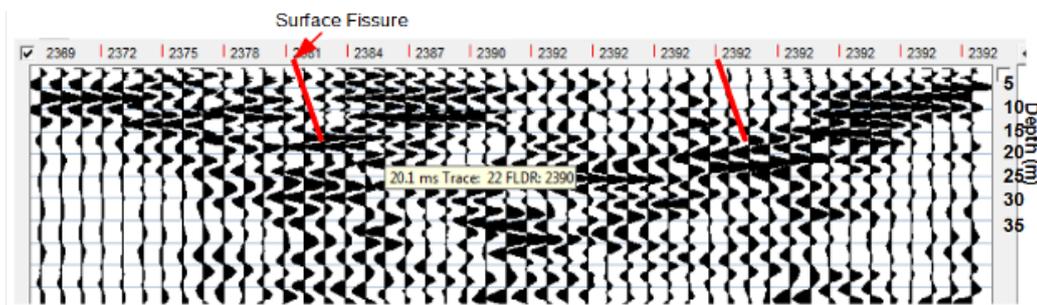


Figure 8: A seismic reflection profile recorded across a visible ground fissure. Note that the fissure continues to a depth of 20 m, indicated with the red lines.

fissures seem to persist to greater depths. Along the length of the profile, the fissures are sub-vertical and show only minimal displacement.

Seismic refraction

A reversed seismic refraction profile was recorded using a symmetric split-spread with two offset shots to enable a better estimation of the substratum seismic velocity. 30 Hz vertical motion geophones were placed at 2 m intervals to make a total profile length of 46 m. The offset shots were placed half the spread length away at 23 m beyond either end of the line. The signal source used in this survey was a 28 lbs. sledge hammer hitting on an aluminium plate. The signal source was stacked 10 times vertically to improve the signal to noise ratio (S/N) by attenuating random noise. Data processing was carried with WinSism™ 10.15 seismic refraction inversion software. Seismic refraction processing involved first break picking and travel time inversion using the ABC delay time method. The first break picking was challenging because of the poor signal quality caused by high signal attenuation.

Figure 7 is a seismic refraction profile showing a two layer velocity model comprising overburden with a seismic velocity of 400-600 m/s lying over another layer with a seismic velocity of 1200-1400 m/s. The top layer consists of the loose sand observed at the surface which is imaged to a depth of 5 m across the profile. The bottom layer with a seismic velocity of 1200-1400 m/s constitutes more compact and saturated material. The fine sand in the depressions was observed to contain a calcareous cement, which may be responsible for the better compaction, and hence a higher seismic velocity.

Seismic Reflection Profiles

Seismic reflection data were recorded with an equal source and

receiver interval of 1 m, as required for common mid-point (CMP) data recording [15], and a total line length of 23 m across one large fissure developed parallel to a paved road. The geophones were kept stationary while the source was moved through the spread. This arrangement led to a good fold of coverage and hence good S/N improvement during stacking. The source signal used in this survey was a 28 lbs. sledge hammer hitting on an aluminium plate. The source signal was stacked 10 times vertically to improve the S/N by attenuating random noise. The sledge hammer signal produces a broad high frequency bandwidth which is ideal for high resolution work. However, problems were experienced with high signal attenuation caused by the loose surface sand.

Seismic reflection data were reduced using Visual_SUNT™ 12. Seismic reflection processing followed the standard CMP processing sequence, including both spiking and predictive deconvolution to improve temporal resolution. Figure 8 shows seismic reflection profile recorded perpendicular to the road across a large fissure developed on the edge of the road. This profile achieves a lateral resolution of 0.5 m. The profile shows that the ground at this location consists of sub-horizontal layers from 0-15 m, which have all been broken by the surface fissure observed at the surface.

Discussion of Results

The Karoo Supergroup in Letlhakeng is represented by the lower Ecca Group, comprising mudstones and carbonaceous shales. Below the Kalahari sand occur weathered mudstones of the Lower Ecca Group. These mudstones weather to clay, which in this case is of the expansive type. The expansive clay is exposed on the fossil valley floor in Letlhakeng where it forms black cotton soil but elsewhere it sub-crops below 4.5-5 m of loose sand. Examination of the GoogleEarth™

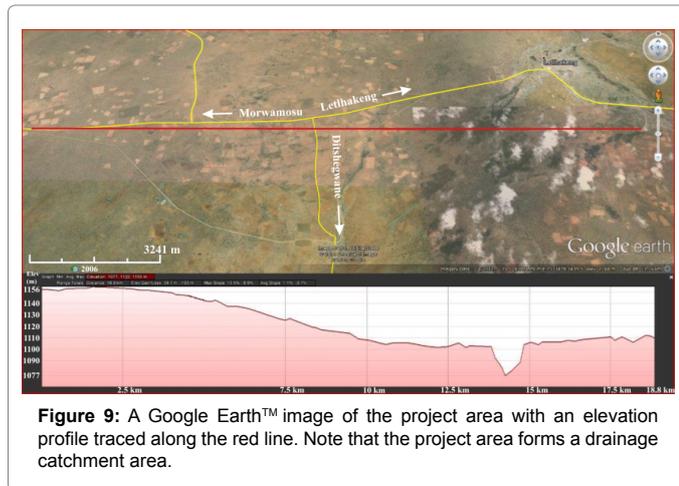


Figure 9: A Google Earth™ image of the project area with an elevation profile traced along the red line. Note that the project area forms a drainage catchment area.

image in Figure 9 which includes an elevation profile shows that the topography is flat to the west of Sesung village, but it decreases rapidly towards the east. The implication of this is that during the wet season surface water percolates through the loose sand and is stopped by the impermeable clay at a shallow depth of ~5 m. This water accumulates and then forms a base flow in the direction of decreasing elevation, and the flow is impeded by the presence of sand. The water will thus reside in the sand for a long time and wet the clay, enhancing its weathering, and also causing it to expand. As the dry season progresses, the clay will dry out and shrink, causing the development of desiccation cracks. The desiccation cracks manifest themselves at the surface as ground fissures. At the valley floor, where the clay is exposed, the desiccation cracks develop much earlier as the groundwater level recedes. The damage on the civil structures such as paved road occurs in two ways; on the valley floor the damage occurs as the clay dries out since they are in contact with it. Where the clay occurs below sand, liquefaction occurs when the loose sand is saturated and the structures collapse into it and later also when the clay dries out.

Conclusions

Based on the arguments presented in the previous sections, it is concluded that the cause of the ground fissures in the Letlhakeng area is the cyclic wetting and drying of weathered mudstone which is exposed in the valleys and covered by up to 5 m of loose sand away from valleys. The damage affecting infrastructure occurs due to desiccation cracking and also loss of support when the mud liquefies from excess saturation.

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