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ABSTRACT

The process for oil drilling through superficial deposits often results in ground movements. However, because of the rapid sequence of the operations, these movements are hardly noticed or monitored. Oil drilling is generally carried out over drilling slabs or platforms. Such a slab was constructed on a land location close to the Imo River in Niger delta of Nigeria. During the process of drilling over the slab, large depressions around the cellar pits were noticed. This development demanded the lowering of the rig and an investigation into the causes of the movements was initiated. The investigation confirmed the existence underneath the slab of sandy clay overlying badly sorted sandy gravel occasionally interbedded with thin argillaceous seams. The ground water table was high. The mean percentages of sand and gravel in the deposit were 20 and 80 percent respectively. This poor combination of sand and gravel gave rise to instability within the deposit. The drilling process, which had considerable disturbing effects on granular deposits, caused the sand to migrate to fill the interstices formed by the gravel particles with consequent creation of subsurface voids, which were the main contributors to the subsidence.

INTRODUCTION

The onshore oil and gas industry in Nigeria makes extensive use of drilling slabs for its land exploration. The drilling rig and the drilling tools are mounted on the slab. A typical drilling slab is a reinforced concrete structure about 30m long, 12.5 wide and 0.25m thick. An opening designated as cellar pit is usually provided on the slab through which the borehole is advanced using rigidly connected drilling rods. During drilling, the slab is essentially subjected to vertical loads ranging between 100 and 150kPa. These loads most often cause some movements of the slab. However, because of the rapid sequence of the drilling operation, the movements are hardly noticed particularly where the slab is not subjected to any appreciable distress. Nevertheless, large total and differential settlements, which may likely cause the collapse of the slab, are unacceptable. Collapse of drilling slabs often results in colossal human, economic and material implications.

An old drilling slab over which oil exploration had previously taken place was lifted and replaced with a new one in a land location. The new slab was provided with two cellar pits. The new boring point on the slab was 5m away from the existing one. The project site was close to the confluence of two rivers- the Imo River and the Otamini River. These rivers are noted for the substantial deposits of alluvium that rim their courses.
During the process of installing the stovepipe, in preparation for the drilling, large depressions around the cellar pits were noticed. This unexpected development demanded that drilling activities be discontinued. This paper describes the historical background of the subsidence, the findings of the subsequent investigations and the analytical studies of the causes of the subsidence.

HISTORY OF EVENTS

The selected location for the exploration was an existing one. Oil exploration had taken place at this location before and all drilling activities went off smoothly without any mishap. The new drilling point was established 5m from the existing one. The new slab occupied the same area as the old one but only longer and containing two cellar pits. When it was decided to carry out the exploration it was thought that there was no need for any ground investigation since the previous exploration was carried out without any noticeable ground problem.

Drilling activities over the new slab commenced on 10 January 1991 with the installation of the stovepipe. The stovepipe was 650mm in diameter and was to be driven to a depth of around 150m. The main function of the stovepipe was to protect the borehole from collapsing material. Drilling for oil usually takes place after the installation of the stovepipe. However, after the stovepipe had been driven to a depth of 48m, ground subsidence was observed around the cellar pits. Drilling activities often center on the cellar pits. This unexpected development took place on 12 January 1991, two days after the commencement of the drilling activities. Driving of the stovepipe was discontinued and the rig mast was lowered.

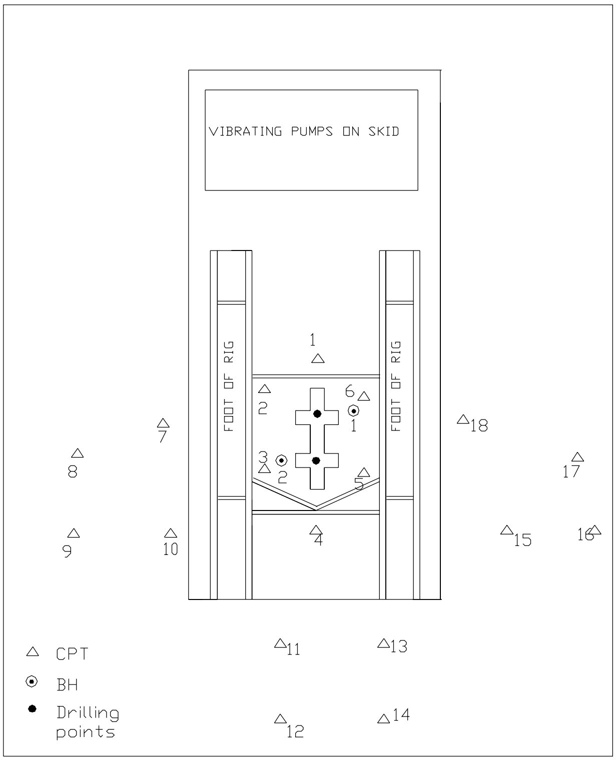

Fig. 1 Typical drilling slab showing cellar pit and positions of geotechnical boreholes and cone penetration tests

Fifteen monitoring stations were established on the slab. Eight of the stations were around the affected zone and seven of them some distance away from the cellar pits. The movements were determined using precise levelling technique. The initial movements were sudden and differential and ranged between 130 and 148mm with an average of 140mm. The sudden subsidence was ascribed to voids immediately under the drilling slab and attempts were made to stabilize the ground by means of cement grouting. Grouting process was completed in three days and a decision was taken to stand the mast and continue with the installation of the stovepipe. The effectiveness of the ground improvement was closely monitored. At the time the stovepipe had penetrated 70m, further movements were noticed and the subsidence had increased to an average depth of 185mm below the original elevation of the surface of the slabs. The end walls of the cellar pits had separated at about the joints of the structural elements and average opening of 12mm was recorded. At this time, the slab was becoming highly distressed and the collapse of the slab was imminent. It was decided to discontinue the drilling activities at the location. The rig was brought down, disassembled and moved to another location on 22 January 1991.

SITE DESCRIPTION AND GEOLOGY

Regional Geology

The site for the oil exploration is located southeast of the Niger Delta and a few kilometers from the confluence of the Imo river and the Otamini river. The southern basin of Nigeria has been the scene of at least three major depositional cycles since its inception in the Early Cretaceous time. The first cycle commenced in pre-Albian time and involved mainly marine deposition within the basin. This cycle ended with a brief phase of folding of Santonian age. The second cycle began with a Campanian marine transgression and included the growth of pro-Niger Delta in the northern part of the basin. This cycle ended with renewed widespread marine transgression in Paleocene time. The basic framework of the present delta was built on the past two cycles. The third cycle included the time when the Niger Delta prograded towards the near-shore during the Eocene time.

Three main depositional environments have been observed in the subsurface of the Niger Delta Complex. These are Benin, Agbada and Akata Formations. The three formations are considered to be laid down under continental, transitional and marine environments respectively. The Benin Formation extends from the west across the whole Niger Delta and southwards beyond the present coastline. It is coarse-grained, gravelly, locally fine-grained, poorly sorted, sub-angular to well-rounded and bears lignite streaks and wood fragments. It is a continental deposit probably belonging to the upper deltaic environment. Various structural units such as point bars, channel pits, natural levees, back swamp deposits, oxbow fills are identifiable within the formation, indicating the variability of the shallow water depositional medium.

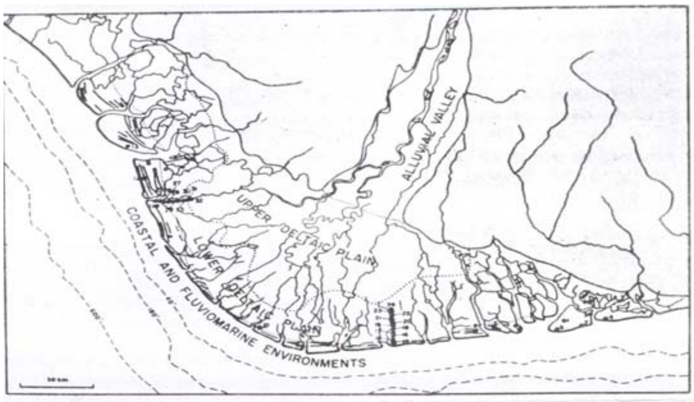

Fig. 2. Late Quaternary Niger Delta Complex, (Oomkens 1974)

The history of deposition in the Niger Delta since the Eocene times is one of cyclic sedimentation involving marine transgressions, erosion and sand deposition followed by a sequence of marine clays, fluvio-marine clays and sands. The cycle is completed with fluviatile deposits.

Site Description and Geomorphology

The project site is located few kilometers north of the confluence of the Imo River and Otamini River. The area is characterized by flat mainly dry and elevated lateritic sandy clay areas and low-lying alluvial plains built by the overflow of the rivers in their search of lines of flow to the sea.

The water table at the site is relatively deep and often encountered approximately at the interface of the sandy clays and the underlying sands and gravels. The sandy clays have been subjected to tropical weathering enhanced by large seasonal variations in moisture. This has resulted in the formation of the near-surface laterized soil, which is typical of the project area.

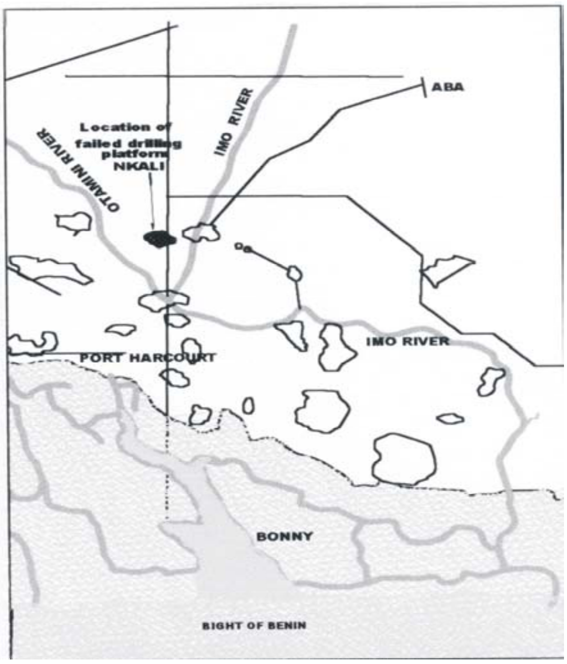

Fig. 3. Location of Site

GEOTECHNICAL INVESTIGATION

Field Investigation

Soil boring and static cone penetration tests were considered to be most useful techniques for the field study of the failure. The field investigation involved the sinking of two geotechnical boreholes within the affected zone. The boreholes were taken down to depths of 40m. Also, eighteen static cone penetration tests were carried out to explore the underlying deposits. Six of these tests were performed around the failure zone and twelve were positioned outside the drilling slab and considered as reference tests. The positions of these data collection points are shown in Fig.1.

The soil borings were carried out using light cable percussion soil drilling rig. Soil samples were retrieved during the boring process at depths of 0.75m intervals from the ground level to the termination of the boreholes. The clayey deposits were sampled with the conventional open-tube sampler 100mm diameter and 450mm long. Standard penetration tests were conducted in the boreholes primarily for the assessment of the relative densities of the granular soils. Split tube sampler 50mm diameter and 450mm long was driven into the soil with a 63.5kg hammer falling freely a distance of 760mm. The number of blows required to effect the last 300mm penetration was taken as the penetration resistance and provided an indication of the relative density of the granular soil layer tested. Figure 4 shows the stratal sequence within the depths explored.

The static cone penetration tests were performed with Gouda-type hydraulically operated static cone penetrometer of 100kN capacity. The equipment consisted of a mechanical mantle cone, sounding rods and a hydraulic device for pushing the cone and the sounding rods into the ground. Pressure gauges were used in

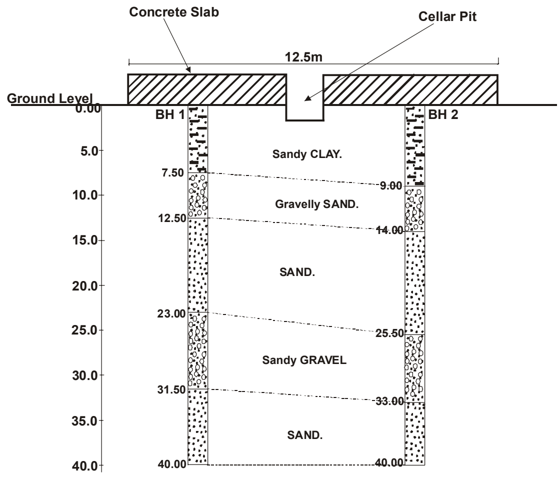

Fig. 4. Soil Profile Around the Failure Zone.

recording the cone resistance. Diagrams showing the cone resistance profiles around the affected zone, on the slab and off the slab are shown in Fig.5.

The natural ground water levels as measured in the boreholes were reasonably constant and were recorded at depths between 8.4 and 8.6m below the ground surface. The recorded ground water levels were typical of the area at the time the field investigation was carried out.

Laboratory Testing

The subsurface materials were collected from the borings to determine their geotechnical properties. Laboratory classification tests were performed on the samples to verify and improve on the field identification and classification. The tests included natural moisture content, unit weight, specific gravity, liquid and plastic limits and particle size distribution. Undrained shear strength tests were also performed on the cohesive specimens for their undrained shear strength parameters.

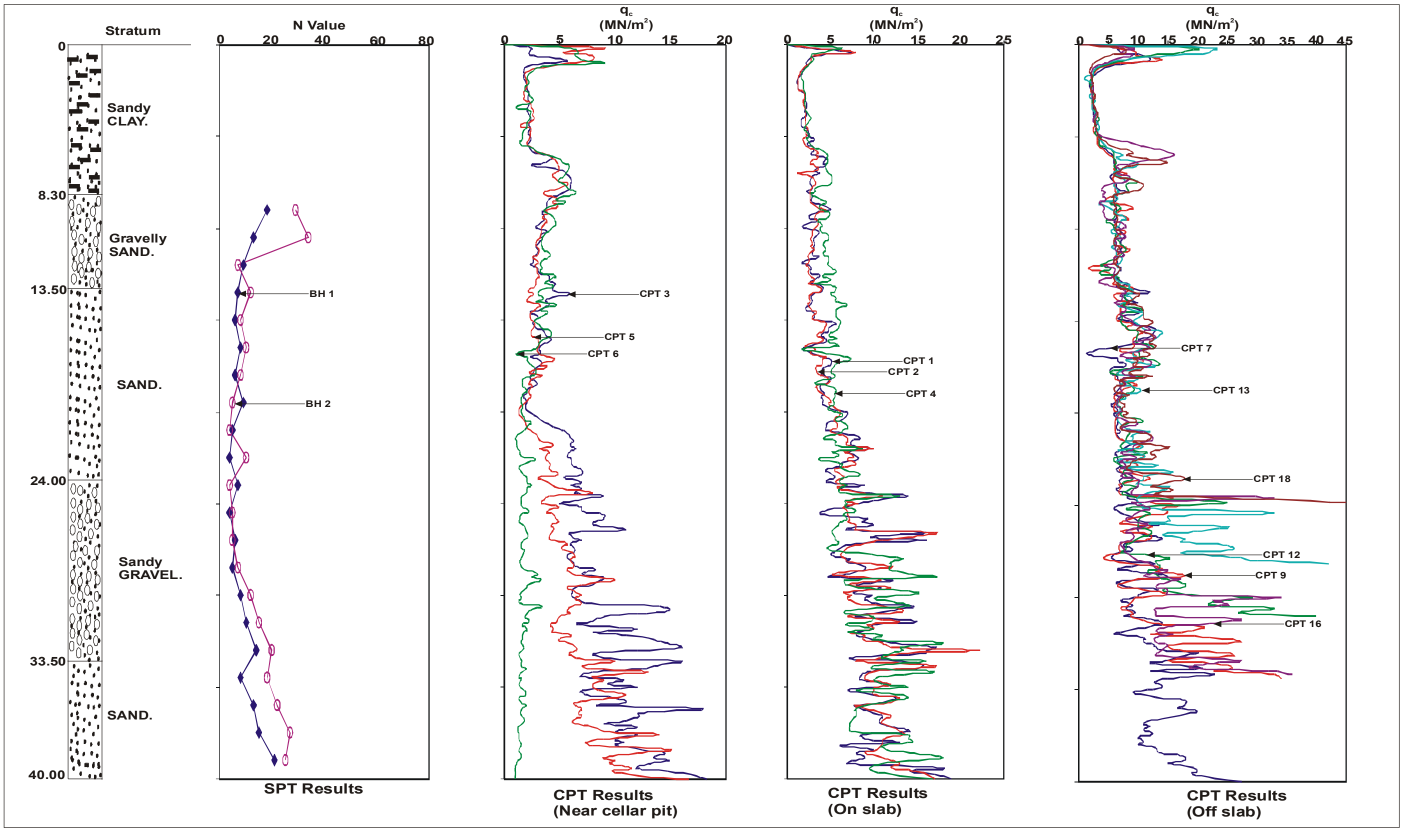

Fig. 5. Sub-Strata and Profiles of In situ Test Results

SUBSOIL CONDITIONS

The affected ground was investigated by borings and in-situ tests. The following stratal succession was disclosed by the borings.

Stratum I A layer of stiff, sandy, lateritic clay with average thickness of 8.3m.

Stratum II Fine to coarse-grained sand, containing proportions of fine to medium gravel ranging between 18 and 44% with the mean of 30%. This deposit is about 5m in thickness.

Stratum III Fine to coarse-grained sand, with dominant proportion of medium grains. The deposit is about 10.5m in thickness.

Stratum IV Fine to coarse, smooth and rounded gravel with some fine to medium-grained sand. The sand proportion within the deposit varied between 8 and 34% with a mean of 19%. The stratum is about 8.5m in thickness.

Stratum V Medium to coarse-grained sand. The deposit extended to the termination of the borehole.

<u>Soil Properties</u>

The summaries of the soil properties of the various deposits encountered within the depths explored are presented in Table 1 and Table 2.

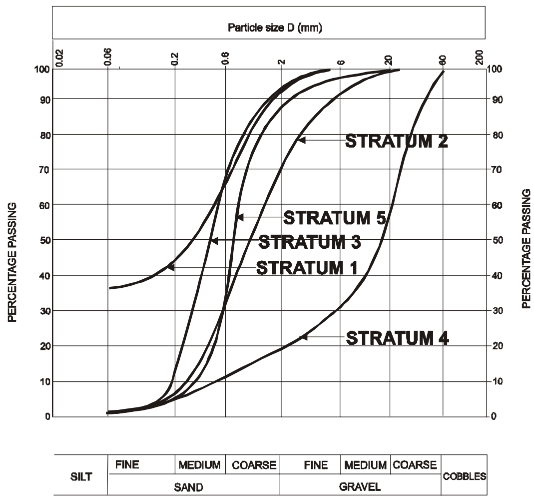

Fig. 6. Median Curves for the Particle Size Distribution of the Various Strata.

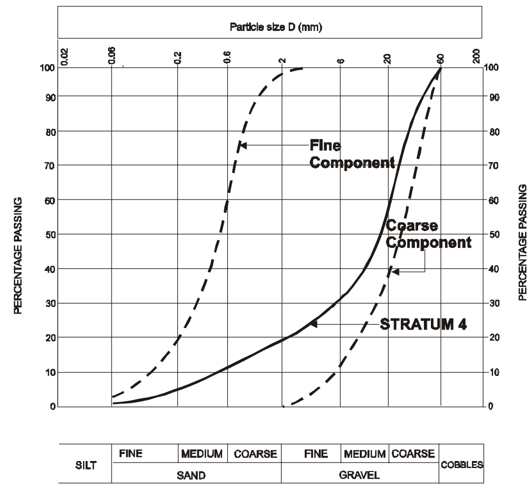

Fig. 7. Grading Curves Showing the Median Curves of the Gravel Stratum and the Curves for the Fine and Coarse Components.

Table 1. Soil Properties of Cohesive Soils

Stratum	Description of Soil	Property	Ranges of Values
I	Stiff Sandy Lateritic Clay.	Natural Moisture Content (%)	10.3 – 13.4
		Liquid Limit (%)	26 – 47
		Plastic Limit (%)	15 – 22
		Plasticity Index (%)	11 - 25
		Bulk Unit Weight (kN/m^3)	19.6 – 21.7
		Dry Unit Weight (kN/m^3)	17.6 – 19.2
		Degree of Saturation (%)	64 - 85
		Initial Void Ratio	0.438 – 0.508
		Undrained Shear Strength (kPa)	42 – 100
		Undrained Angle of Shear Resistance	22 – 28

Table 2. Soil Properties of Cohesionless Soils

Stratum	Description of Soil	Soil Property							
		D_{10} (mm)	D_{15} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	D_{85} (mm)	$C_u = \frac{D_{60}}{D_{10}}$	$C_c = \frac{D^2_{30}}{D_{10}D_{60}}$
II	Gravelly Sand	0.28	0.38	0.62	1.00	1.30	4.80	4.6	0.7
III	Fine to Coarse Sand	0.20	0.24	0.33	0.45	0.53	1.00	2.6	1.0
IV	Gravel with Sand	0.65	1.18	6.30	18.00	20.00	29.50	30.8	3.1
V	Medium to Coarse Sand	0.36	0.43	0.68	0.78	0.90	1.80	2.5	1.1

DISCUSSION

Events leading to the subsidence at the location hinged firmly around the process of the installation of the stovepipe. Depressions around the cellar pits were observed after the stovepipe had descended to a depth of 48m. The subsidence persisted even after the ground beneath the slab had been improved by grouting. Drilling activities were discontinued after the subsidence had attained an average depth of 185mm because of the high risk involved.

Two subsurface exploration techniques, borings and cone soundings were adopted to investigate the subsoil conditions after the subsidence. It was found that a deposit of stiff lateritic sandy clay overlies predominantly sand deposits with layers of gravel intrusions. In-situ penetration tests comprising standard penetration tests and cone penetration tests performed around the distressed zone of the slab gave significantly low values in the granular soils particularly those taken close to the existing drilling point. The cone soundings taken on the slab but away from the failure zone yielded reasonably high cone resistance in the granular soils. The poor state of compaction of the granular deposits was very evident in strata III and IV. Expectedly, the cone soundings taken on the natural ground gave significantly high cone resistance, which was typical of the project area.

Results of the Monitoring

Elevations recorded within the depression created around the cellar pits showed that the settlements at monitoring stations 3 and 6 were comparatively high and these stations were close to the existing drilling point. It was also observed that the settlements obtained at stations B and F away from the cellar pits but on the slab were high in comparison to those at the other reference stations on the slab. It is noteworthy that stations B and F are approximately midway between the existing and new drilling points.

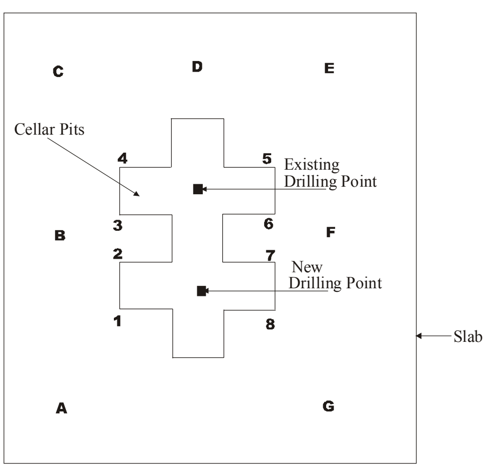

Fig. 8. Showing Monitoring Stations on the Slab

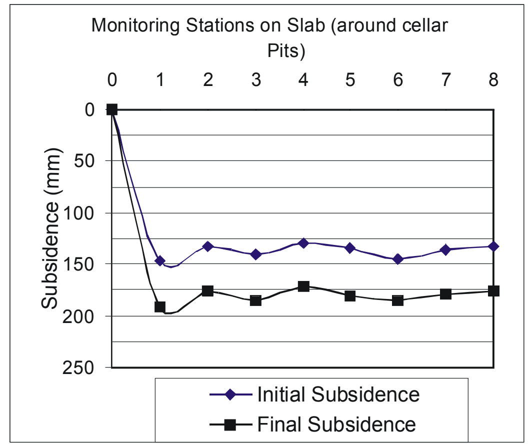

Fig. 9. Measured Settlements around Cellar Pits

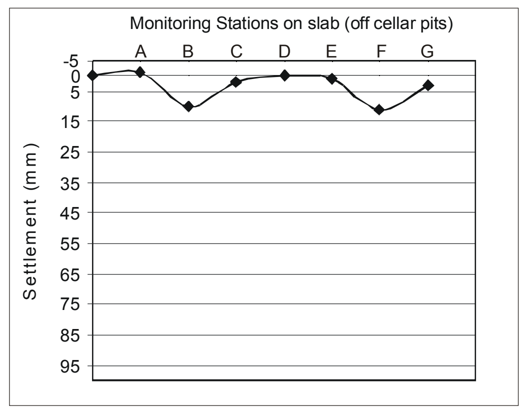

Fig. 10. Measured Settlements away from the Cellar Pits

Causes of Subsidence

The dominant cause of the subsidence is ascribed to the internal instability of the gap-graded sandy gravel, which allowed the migration of sand during the piling process for the installation of the stovepipe. It has been established by researchers that there is a critical content of fines within sandy gravel deposits below which the fines do not fill the voids in the gravel component (Skempton and Brogan). The determination of critical sand content is highly useful in assessing the stability of the sandy gravel deposit. The critical sand content has been quantified in terms of the porosities of the coarse and fine components of the material respectively (Skempton and Brogan).

$$S_c = \frac{n_c(1 - n_f)}{1 - n_f . n_c} \qquad (1)$$

Where S_c is the critical sand content, n_f and n_c are the porosities of the fine and coarse components of the deposit respectively. For this paper the above equation has been modified to an expression containing soil properties easily obtainable from basic soil tests.

$$\mathbf{S_c = \frac{w_c.G_{sc}}{S_r + w_f.G_{sf} + w_c.G_{sc}}} \qquad \mathbf{(2)}$$

Where w_f, w_c are moisture contents of sand and gravel respectively; G_{sf} and G_{sc} are specific gravities of sand and gravel and S_r the degree of saturation of the deposit. With the average laboratory test values of $w_f = 29\%$, $w_c= 22\%$, $G_{sf}= 2.63$, $G_{sc}=2.69$ and $S_r=1$, the critical sand content for sandy gravel deposit was 26%. However, the mean sand content in the sandy gravel deposit was 19%.

Filter criterion was also used to evaluate the stability of the sandy gravel deposit. This criterion states that the ratio of the D_{15} size of the coarse material (filter) should not be greater than four times the D_{85} size of the fine material that is protected. The main functions of a filter are to prevent migration of fine soil grains and at the same time allow drainage of seeping water.

$$\mathbf{\frac{D_{15}(\text{coarse material})}{D_{85}(\text{fine material})} \leq 4} \qquad \mathbf{(3)}$$

The sandy gravel was separated into its fine and coarse components. The fine material was considered as the soil to be protected and coarse component as the filter. The average ratio obtained for the sandy gravel was 9.

Another criterion adopted to assess the stability of the sandy gravel was the value of the coefficient of uniformity, C_u. It has been found that materials having coefficient of uniformity, $C_u = D_{60}/D_{10} > 20$ are highly susceptible to instability. The average coefficient of uniformity obtained for the sandy gravel deposit was 30.8.

It is established that the sandy gravel denoted as stratum 4 in Fig.6 was unstable. There were other ancillary contributors to the subsidence. The instability of the sandy gravel was largely assisted by the vibrations induced in the ground during the piling process for the installation of the stovepipe and the high water table. The conditions were conducive to the migration of sand downwards to fill the gaps within the gravel deposits with consequent creation of subsurface voids in the underlying soil deposits. The downward movement of the slab was in response to the voids created below.

The deformations recorded around the existing drilling point were comparatively high (Figs. 8,9 & 10). This must have emanated from the already disturbed soils around the existing drilling point.

CONCLUSION

There was no geotechnical investigation conducted at the site prior to the oil drilling activities because no ground problems were encountered during the first exploration. Events have shown that such confidence can be highly expensive. Where there is no geotechnical investigation for a project, the ground is often a hazard.

The failure described in this paper is relatively rare. Granular soils, even gap graded sandy gravels are considered as competent load bearing materials when the loads are static. However, where the loads involve vibrations, collapse of such poorly graded materials as foundation soils should not be ignored. Great care is needed in interpreting the bearing strength of the poorly graded soils where the foundation may be subjected to vibrations. This failure shows vividly that land oil explorations close to existing drilling points should be carried out with extreme caution because of the uncertainties in the prevailing state of the underlying soil deposits after the exploration.

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