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Laboratory foundation model with pyrite-bearing mudstone fill

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Abstract

Damage to domestic dwellings in the greater Dublin area of Ireland engendered by the expansion of underfloor fill material containing pyrite has become a high-profile national problem in recent years. In this paper, a novel physical model is described in which the profile of underfloor materials representative of Irish construction practice is modelled; the relevant vertical dimensions are at full scale. The study has enabled the rate of pyritiferous expansion to be ascertained over a period of 830 days at laboratory temperatures; rates of 0.0021 mm/mm.yr and 0.0008 mm/mm.yr were observed with no loading and a pressure of 3.4 kPa on the concrete slab respectively. The rates of expansion are broadly consistent with those found from reference pipe experiments. These data are an important frame of reference for anticipating the time required to generate a specific amount of floor movement in domestic dwellings. Pressures generated within the fill are low and consistent with the occurrence of significant expansion.

1. Introduction

In the early years of the 21st century, the Republic of Ireland experienced rapid economic growth which was significantly influenced by a buoyant construction industry. In 2007, the construction industry employed approximately 400,000 people and accounted for 23% of the Gross National Product (Tuohy *et al.,* 2012). These figures were significantly driven by house-building, with the number of housing units completed in a calendar year peaking at 88,188 in 2006 compared to 30,575 in 1995 (Central Statistics Office, 2008). Tuohy *et al.* (2012), quoting the Irish Concrete Federation, noted that the increased rate of building meant that 1200 quarries were in operation in the mid-2000s with some "*opportunistic supply of materials without the necessary technical knowledge at specifier, user or supplier level*".

Some of the quarried fill material deployed in house foundations in the east of Ireland contained pyrite (FeS_2), a naturally-occurring mineral that oxidises to form products including sulphuric acid (H_2SO_4) upon access to water and oxygen. Sulphuric acid reacts with calcite ($CaCO_3$), another common mineral constituent, to generate gypsum ($CaSO_4 2H_2O$). The complex reaction process is detailed by Reid *et al.* (2005) and while represented by the chemical equations in Appendix A, some stages require activation by bacteria. The generation of gypsum gives rise to an increased fill volume compared to the original pyrite and calcite. Volume increases in pyrite-bearing fill used in house foundations may result in heave of ground-bearing floor slabs and lateral displacement of foundation walls, leading in turn to significant damage to the superstructure, including cracking floors and walls, jamming doors, buckling of interior partition walls and movement of stairs. A useful schematic diagram of the process is presented in Czerewko and Cripps (2015). The number of housing units in Co. Dublin and surrounding counties founded on fill material with the potential to result in heave damage was established by Tuohy *et al.* (2012) to be 12,250 in 74 estates.

The expansive behaviour of pyrite-bearing mudstone fill has been confirmed in laboratory experiments at NUI Galway and factors influencing the expansion have been examined (Sutton *et al.*, 2013, McCabe *et al.*, 2015, McKeon, 2015). These studies used fill retrieved from beneath the floor slabs of dwellings in the greater Dublin area exhibiting structural distress. Samples were re-established in PVC pipes standing vertically in plastic basins with varied depths of water in the basins. Sutton *et al.* (2013) prepared ten such pipes with constant density (approx. 2000 kg/m^3) using fill from the same source and varied the height of fill and the depth of water (i.e. the submerged depth). The tests were carried out in an unheated laboratory and therefore the ambient temperatures showed a clear seasonal influence, generally increasing from a minimum of 4°C to a maximum of 15°C. It was found that the magnitude of heave was proportional to the fill depth during the 6 month period of testing. The submerged depth was found to have little effect. Using fill from a different source, McCabe *et al.* (2015) reported on six further tests using the same apparatus with constant fill heights, varied densities (1800 kg/m^3, 2000 kg/m^3 and 2200 kg/m^3) and varied water depths, situated in a temperature-controlled room with hold periods at 10°C, 15°C and 20°C over the duration of testing. The authors concluded that the density of the fill affects the onset time and/or the magnitude of heave; higher density gives rise to faster/greater heave. It was also reported that there was no long-term effect of temperature on the rate of heave over the temperature range tested (i.e. between 10°C and 20°C) once the effects of thermal expansion of the testing system were accounted for. In these experiments, the use of smooth pipes and the absence of vertical loading on the fill represented a deliberate attempt to encourage the maximum amount of expansion, although no attempt was made to accelerate the oxidation process. In this regard, the Sutton *et al.* (2013) testing approach has been referred to by Hoover *et al.* (2015) as 'passive expansion testing', as distinct from their accelerated kinetic testing (in humified air to which 10% carbon dioxide was introduced) and hydrogen peroxide expansion testing (10% hydrogen peroxide solution introduced) approaches.

In this paper, an original laboratory foundation model is described, which encapsulates a greater volume of fill than the pipe experiments and replicates more closely the underfloor conditions typical of an Irish dwelling. The concrete block perimeter of the model represents the rising walls and encloses a vertical profile of materials from the *in situ* soil to the concrete floor slab, including some pyrite-bearing fill material. In addition to heave of the slab, the pressures generated and relative humidity within the body of fill were investigated over a period of over 27 months. Three pipe experiments (of the type described by Sutton *et al.*, 2013 and McCabe *et al.*, 2015), using fill from the same batch incorporated in the foundation model, were conducted in parallel as a frame of reference.

2. Experimental Arrangements

2.1 Foundation Model Composition

The NUI Galway Pyrite Foundation Model consisted of the masonry box structure shown in Figures 1a and 1b with internal dimensions of 1.125 m (length) × 1.125 m (width) × 0.770 m (height). The masonry blockwork was constructed on two abutting precast concrete slabs, raised slightly off the ground for ease of access to lifting equipment. The walls of the foundation model consisted of seven courses of standard 4-inch (100 mm) concrete blocks built on the flat face giving a 210mm-thick wall consistent with conventional rising wall construction in Ireland. The mortar used for jointing was a mix of Ordinary Portland Cement, sand and water in the ratio of 2:6:3.

A schematic of the vertical profile of materials/finishes A-K and M in the model is shown in Figure 2. With the exception of the underlying clay layer, the vertical thicknesses (where relevant) are unscaled. Details are provided below:

<u>A: Bituminous seal:</u>

A bituminous seal was applied internally to the base and to the block walls up to the level of the underside of the concrete slab (i.e. 600 mm above the base) with a view to inhibiting any moisture escape into the blockwork and drying of the fill. In particular, the seal along the four sides was intended to provide comparable boundary conditions to those produced by the concrete-filled cavity between the rising walls of adjoining (semi-detached or terraced) dwellings.

B: Compacted clay:

The clay was sourced from the foundation of a house undergoing remediation for heave damage in north Co. Dublin. The moisture content at the time of foundation model construction was found to be approximately 19%, while values of plastic limit and liquid limit were established as 17% and 35% respectively. These values are consistent with those of Upper Brown Dublin Boulder Clay (Menkiti and Long, 2007) which occurs widely in the Dublin area at the depth at which houses are founded.

The clay was spread evenly on the base of the model and compacted in one layer (final thickness 100 mm) to approximately 2000 kg/m^3 using a bespoke 15 kg tamper. Between the end of compaction and the addition of the overlying fill layer (C), the clay was temporarily covered with a plastic membrane to prevent moisture loss.

C: Pyrite-bearing mudstone fill:

Fill thicknesses beneath floor slabs of domestic houses are typically in the range 400-600mm; 400mm was adopted for this experiment. The target density of the fill was approximately 1800kg/m^3, in keeping with values back-calculated by Aidan O'Connell and Associates Ltd. upon weighing the entirety of fill removed from beneath a floor slab and determining accurately the volume of space vacated. Compaction was achieved using the same tamping device that was used for the clay. The fill was placed and compacted in the model in 7 sub-layers, each 55 mm - 60 mm thick, taking care that few fill particles were crushed during the compaction process. Details of the relative humidity probes and pressure cells installed within the fill are provided in Section 2.2, while a detailed description and characterisation of the material is provided in Section 3.

D: Blinding sand:

The target density of the sand was 1600 kg/m^3. Five no. 20 mm dia. holes were drilled in each of the four side walls at a level corresponding to mid-depth in the sand. These holes were intended to facilitate access to air as provided by radon ventilation in real underfloor environments.

E: 1200 gauge Damp Proof Membrane (DPM):

This plastic DPM inhibited any moisture egress through the insulation or concrete slab above, as is standard construction practice (indicated by dashed line in Figure 2). The DPM was continued upwards along the interior face of the model walls and was sealed on the outside of the model as can be seen in Figure 1a, essentially ensuring a complete moisture seal.

F: High density insulation:

Kingspan Kooltherm K3 Floorboard, 50 mm thick, was used and cut to fit snugly on top of the DPM.

G: Concrete slab:

A precast hollowcore concrete slab (mass 303.9 kg) was placed on top of the insulation. The slab measured 1.075 m × 1.075 m in plan by 150 mm in thickness. Elements D, F and G imposed a combined vertical stress of 3.4 kPa on the fill.

H: Insulation strips:

In the 25 mm surrounds between the walls of the model and the slab, cold bridging insulation strips were fitted and any gaps were filled with expanding foam.

J: Screed:

A self-levelling screed was poured on top of the slab to give smooth contact points for the dial gauge tips.

K: Imposed load:

Floor slabs in standard domestic dwellings are required under I.S. EN 1991-1-1: 2002 to cater for a live load of 1.5 kPa. An external load was imposed approximately 17 months after commencement of the experiment using concrete blocks of nominal dimensions 95 mm × 95 mm in section by 445 mm long (known colloquially in Ireland as *soap bars*). A total of 50 of these blocks (some split into two) provided an average loading of approximately 3.4 kPa over the slab, i.e. doubling the stress already supported by the fill owing to the weights of D, F and G and deliberately surpassing the 1.5kPa value so as to induce a clear response. As can be seen from Figure 1b, the positions of the blocks were dictated by the positions of both the dial gauges and reference beam and the requirement of a clear line-of-sight to the dial gauges; the plan area coverage was approximately 71%.

A Water Tank (L) was also provided outside the model with its base 400mm above the top of the clay layer. The tank could be connected to a 'Weeping Pipe' (M) irrigation facility which was laid at the interface of the clay and fill, intended as a means of replicating the source of water that may be available from the clay in field situations. However, since the rate of heave showed no evidence of abating over the 27 month test period, this irrigation facility was not utilised.

The model was situated adjacent to an external wall in the Soils Laboratory at NUI Galway. The proximity to windows (which opened and closed automatically in response to temperature and carbon dioxide levels in the laboratory) allowed fresh air to circulate around the model.

2.2 Foundation Model Instrumentation

2.2.1 Relative Humidity Probes

Relative humidity (R.H.) probes were used to help signal any changes in moisture within the fill, the net effect of some or all of the following: fill drying, consumption of water in the reaction and replenishment of water by migration from the clay. The GE Sensing devices (product no. BLD4750) had relative humidity ranges of 30-100%, with an accuracy of ±3% in the range 30-40% and an accuracy of ±2% for relative humidities greater than 40%. The positions of four sensors RH1-RH4 are shown in Figure 3a. All sensors were located 227mm from the side walls. Two probes RH1 and RH3 were positioned in diagonally-opposite locations with mid-level at 300mm below the top of the fill while the other two diagonals were occupied by sensors RH2 and RH4, with mid-level at 100mm below the top of the fill. The fill surrounding the probe housing (Figure 4) was sieved and only particles larger than 5mm were placed within 50mm of the probe. This ensured that little deleterious matter passed through the 5mm dia. holes in the housing reducing the chance of clogging or damage to the probe. Each cable was sealed in a rubber covering to avoid damage.

Small containers of fill material were used to develop calibrations between relative humidity and moisture content for RH1-RH4 prior to their incorporation within the foundation model. Initially a coarse calibration (with large increments of moisture content in the moisture content range 1% and 10%) was carried out which revealed that:

(i) at moisture contents above about 4%, the relative humidity remained in the range 90-95%, rendering 4% moisture content as the upper limit of applicability of the humidity sensors.
(ii) below 4% moisture content, the calibrations were repeatable and non-linear.

In relation to (i), Taylor *et al.* (2013) report a similar experience of limited range of usability of humidity sensors in pyrite-bearing fill, albeit at a lower limiting moisture content. In keeping with (ii), Jiang and Yuan (2013) also established that the relationship between the relative humidity of an air pocket in a concrete cube sample and the moisture content was non-linear.

A finer calibration was subsequently carried out in the moisture content range 2.5% and 4.5% and is shown in Figure 5 for RH1, RH2 and RH4 (RH3 malfunctioned when incorporated within the model). Each of the probes RH1-RH4 also recorded temperature (accuracy ± 0.3^0C).

2.2.2 Pressure Cells

Two-single sided (P6-2.1-MS-10-T) and one double-sided (P6-1.1-SS-10-T) circular vibrating wire pressure cells (from ITM Soil Instruments, U.K.) were installed in the Foundation Model. The external diameters of the single-sided and the double-sided cells were 240mm and 200mm respectively, while the active face (i.e. the area measuring the pressure) was 176mm for both types. The pressure range of all three cells used was 0-1 MPa in allowance for the possible development of high stresses (damage to Golder Swell Test chamber used by Maher *et al.* (2011) was calculated to have required a pressure of 600kPa) with an accuracy of 0.1% of full scale (=1 kPa). Each cell also incorporated a thermistor (with range -20°C to 80°C) with an accuracy of 0.5°C.

The arrangement of pressure cells within the foundation model is shown in Figure 4a. One single-sided pressure cell (PC1) was placed vertically against the block wall, with active side facing out and centred at mid-height of the fill and at mid-length of the wall. The double-sided cell (PC2) was placed horizontally at the mid-height within the fill and centred in plan. The second single-sided cell (PC3) was placed with active side facing down at the interface between the sand layer and insulation. The proportion of the plan area of the fill occupied by the faces of cells PC2 and PC3 was 3.6% and 2.5% respectively and therefore their presence was not believed to have interfered significantly with the expansion process. Only particles passing the 5mm sieve were placed within 25mm of the cells in keeping with the manufacturer's instructions.

2.2.3 Dial Gauges

The movement of the concrete slab was monitored by dial gauges (with an accuracy of 0.002mm), one in the centre of each quadrant of the slab (DG1-DG4) and a fifth near the centrepoint of the slab (DG5), see Figure 1a and Figure 3b. DG5 was added 28 days after the other four in light of the early tilting observed. The dials were mounted on a frame independent of the foundation model walls and slab.

Soon before the imposed load (K) was applied, an additional dial gauge (DG6) was added to monitor potential outward movement of the side wall; this was positioned externally on the opposite side of the blockwork to PC1 and at the same level as its centrepoint (Figure 1b and Figure 3b).

2.3 Reference Pipe Experiments

In order to ascertain the relative performances of the foundation model and the pipe apparatus employed by Sutton *et al.* (2013) and McCabe *et al.* (2015), three pipe experiments D1 to D3 were established using fill derived from the same batch as the foundation model. The pipe setup consisted of HDPE pipes (229 mm in diameter) each placed vertically in the centre of a 45 L (570 mm x 390 mm x 280 mm) plastic storage box. The pipes were filled to a height of 500 mm with fill compacted manually in 100mm layers to approximately the same density as the foundation model using a 7 kg tamper, again taking care that few particles were crushed during the compaction process. The fill was topped with 50 mm of compacted sand which supported a 3 mm thick and 200 mm diameter steel plate. No additional loading was applied. An independently-supported dial gauge resting on the steel plate was used to measure the expansion of the fill. The pipes incorporated two rows of 10 mm diameter holes drilled 60 mm and 100 mm from the top of the sand to give the fill access to air with another two rows drilled 25 mm and 10 mm from the bottom of the pipe to give the fill access to water if supplied in the basins.

Test D1 was located in the same temperature-controlled room as tests B1-B6 described by McCabe *et al.* (2015) and was therefore subject to a nominal temperature of 20^0C for the vast majority of the testing period. Replicate tests D2 and D3 were located in very close proximity to the foundation model in the open laboratory (Figure 6) and were therefore exposed to the same temperature and humidity variations. The first expansion readings from these pipes were taken 28 days after the first expansion readings from the foundation model.

2.4 Water supply

In both the foundation model and the pipe apparatuses, the option to supply additional water was available through the irrigation system (M) and the plastic storage boxes respectively. A 10 mm depth of water was supplied to the basins at the outset of the pipe experiments and replenished as needed for approximately 10 months. However, given that no external water had been supplied to the Foundation Model by this time, and that previous pipe experiments at NUI Galway have shown that the expansion reaction can be sustained for years by the natural moisture content of the fill alone, it was decided to discontinue water supply to the pipes for compatibility between the two experiments thereafter. At the time of writing, heave rates in the pipes and Foundation Model had shown no sign of abating, so no additional water was supplied.

3. Mudstone Fill Properties

3.1 Introduction

The fill sample used in the foundation model and in the reference pipe tests D1-D3 was a crushed rock aggregate that had been originally sourced from a quarry in the lower Carboniferous age sequence in the Dublin environs where this constitutes the bedrock. This fill was quarried and placed in 2005. In May 2012, material was sampled from a property that was suspected to be suffering from the effects of heave. The identification, descriptive and analytical work was carried out in 2012 by Sandberg LLP Laboratories, London, on representative samples of the fill. Remediation began approximately one year later, at which time samples were taken for use in this study. It should be noted that this material came from a different source to that used in the tests reported by Sutton *et al.* (2013) and McCabe *et al.* (2015).

3.2 Grading, Density and Moisture Content

The grading for two fill samples largely conformed to National Roads Authority (NRA) Clause 804 bounds at the time of the laboratory experiments as shown in Figure 7, although it is possible that some breakdown of the material occurred during placement, compaction and subsequent re-excavation. The sample was described as a sandy GRAVEL, consisting of a homogeneous mixture of calcareous mudstone, argillaceous (muddy) limestone and carbonaceous limestone. The fill comprised fragments up to about 60 mm in size and with less than 10% of silt-sized particles. The larger particles tended to be flat and were orientated with the maximum dimension in the horizontal direction and did not span a full sub-layer during compaction in the foundation model and pipes.

Profiles of initial fill density and moisture content (determined by drying at 105^0C) in the Foundation Model and the pipes at the time of the experiment are shown in Figure 8. For reference, a single moisture content determination of 4.6% (determined by air-drying at 38^0C) was reported for fill in the same dwelling (Sandberg LLP 2012).

3.3 Lithology

Based upon the examination of a hand specimen and a thin section prepared from a representative crushed 0.25-4mm fraction, the fill was comprised as follows:

Lithology 1: Calcareous mudstone (approximately 71%)

The individual fragments consisted of tabular shaped, medium to dark brownish grey, weak to very weak calcareous mudstone with laminae of silty mudstone and medium grey carbonaceous mudstone. Most particles were of low porosity but occasional porous zones with abundant openings along grain boundaries were present. The particles were composed of predominantly clay-grade sheet silicate minerals, quartz and calcite and they contained varied amounts of silt-grade particles of quartz and calcite. Framboidal pyrite was abundant and many of these grains were surrounded by reddish-brown alteration rims.

Lithology 2: Argillaceous (muddy) limestone (approximately 16%)

The fragments consisted of strong, medium to dark brownish grey laminated and non-laminated predominantly blocky limestone and argillaceous, in parts silty and carbonaceous limestone with a continuous gradation in composition between the argillaceous limestone and calcareous mudstone. The particles consisted of varied mixtures of sheet silicate minerals, clay and silt-grade calcite and quartz particles and small amounts of carbonaceous matter. Many particles contained pyrite cubes and framboidal pyrite; the former were more common in the more calcareous particles and the latter tended to be most abundant in the more argillaceous laminae and particles.

Lithology 3: Limestone (approximately 5%)

The fragments were composed of strong, medium grey, blocky low-porosity particles of mainly micritic limestone containing some sparry calcite and some carbonaceous matter. Occasional silicified and chalcedonic patches consisting of milky or greyish quartz were also present together with carbonaceous matter and traces of pyrite grains.

Silicified limestone, quartzite and gypsum crystals were also present and the surfaces of the fill particles were covered in abundant calcareous and argillaceous dust with brown staining probably derived as an alteration product. XRD analysis of a powdered representative sample indicated that pyrite and gypsum were present and chemical analysis implied that there was 1.1% pyrite and 7.4% by weight of gypsum in the whole rock. The gypsum was present as discontinuous surface coatings of crystals, in the fines adhering to particles and also infilling cracks in about 17% of mudstone particles.

3.4 Chemical Testing

Chemical test results are set out in Table 1; values in bold have been calculated based on equations set out in Reid *et al*. (2005). The calculation of original pyrite content assumes that all sulphur (S) was originally in the form of pyrite; in general, there may be some S present in organic matter. The calculation of existing pyrite content assumes that all S liberated from pyrite is now present as Acid-Soluble Sulphate (AS) and not lost in groundwater. Although IS 398 (NSAI 2013) was not in force at the time of construction, this fill exceeds the current limits for Acid-Soluble Sulphate AS (0.2% SO_4), Water-Soluble Sulphate WS (1500 mg/L SO_4) and Total Sulphur TS (1.0% S) specified in the standard. The values of TS and the proportion of mudstone in the fill are illustrated in Figure 9 for this material in the context of test results from other properties in the same development, which were also derived at the Sandberg LLP laboratory. While this figure indicates the variability of the material used across the development, there is a clear correlation between the TS value and the proportion of mudstone in the fill.

4. Results and Discussion

4.1 Temperature readings

The ambient laboratory temperature is recorded by the Building Management System (to an accuracy of 0.3^{0}C) and varied in the range 18^0-25^{0}C until August 2015 (Figure 10); thereafter temperatures were not logged due to a malfunction. Also plotted are the temperatures recorded by the pressure cells and the humidity sensors within the foundation model which clearly follow the same pattern, with temperatures recorded by PC1-PC3 and RH1-RH4 typically falling 1.5^{0}C and 2^{0}C below the recorded ambient temperature respectively. These temperature data were valuable in assessing the extent of thermal expansion of the foundation model and pipe experiments D2 and D3; the room temperature was used to estimate the thermal expansion of the reference frame and dial gauges whereas the internal temperature measurements were used to determine the thermal expansion of the internal materials (including the fill).

The coefficient of thermal expansion of the fill was assumed to be equal to that measured for a pyrite-free Clause 804 fill material (15×10^{-6} / ^{0}C) established in two additional pipes as part of this research (McKeon 2015). Standard published values were used for other materials.

Temperatures in the temperature-controlled room, relevant to pipe D1, varied between 19.0^{0}C and 21.5^{0}C over the period of testing.

4.2 Humidity readings

The variation of humidity with time within the foundation model is shown in Figure 11. Initial humidity readings for RH1, RH2 and RH4, taken once the foundation model was fully established, were all in the range 60-70%, which imply moisture contents (slightly below 3%) which are compatible with those measured directly for the fill in the foundation model (Figure 8). The subsequent variation of relative humidity with time for RH1, RH2 and RH4 is shown in Figure 11 from which it is observed that:

(i) Sensor RH1 registered an increase in humidity to 92-93% within about 15 days and remained stable thereafter. The increased moisture content in the fill is evidently drawn from the clay 100mm below, but the actual value cannot be determined with certainty due to the calibration issue discussed in Section 2.2.1.

(ii) Sensors RH2 and RH4, both 300mm above the clay layer, showed a more gradual increase in humidity to values in the range 80-85%. The inferred moisture contents for RH1 and RH2 are also shown in Figure 11; representing increases of the order of 0.25% from the initial values.

Given the stable output from the sensors, only intermittent readings were deemed necessary beyond the 270-day mark to confirm that the irrigation facility was not required.

Relative humidity values in the temperature-controlled room varied between 57% and 88% and may provide an explanation for differences between the behaviour of D1 and the other two pipes.

4.3 Heave

4.3.1 Foundation model

The absolute displacements registered by all five dial gauges on the slab are plotted against time in Figure 12a. Corrections to these movements for thermal expansion of the entire system were calculated and established to be negligible. These data illustrate that some initial tilting of the slab occurred. The curve representing the average of gauges DG1-DG4 indicates that the self-weight settlement and heave due to the pyrite reaction were offsetting each other to some extent for several weeks; thereafter much more consistent heave movements prevailed.

In Figure 12b, the magnitudes of heave are normalised by the fill thickness of 400mm and zeroed at the 45 day mark, the stage at which all gauges were considered to be reflecting upward movement of the slab. With DG3 as a slight exception, all normalised heave rate measurements are very consistent, while that registered by the centre gauge DG5 is virtually identical to the average of gauges DG1-DG4. Before the slab loading was imposed, there appears to be three different periods each having relatively constant rates of uplift (up to day 160, days 160-300, days 300-520). These are explained in Section 4.4 in relation to the pressure cell measurements. In the absence of imposed loading, the average normalised heave rate over a 475 day period (i.e. up to day 520) is approximately 0.0021 mm/mm/yr, or for the 400mm thickness of fill used, a heave rate of 0.86 mm/yr.

Upon application of the imposed load at day 520, all gauges (with the exception of DG2) registered an instantaneous settlement of 0.07-0.1 mm, with minimal additional movement over a 40 day period. Thereafter, heave movements re-established themselves at a reduced rate of approximately 0.0008 mm/mm/yr or 0.32 mm/yr (for 400mm). This reduced rate is in keeping with experience that more heavily-loaded ground floor rooms such as utility rooms and kitchens experience lower rates of pyrite-induced heave than in living rooms and hallways where similar fill is present.

The dial gauge mounted on the side wall DG6 registered no discernible movement over the period for which it was in place. Additionally, a visual inspection of the blockwork and joints showed no evidence of deterioration over time.

4.3.2 Pipe experiments

The movements registered by all pipes D1-D3, normalised by their fill heights of 500mm, are plotted on Figure 13 (the time origin on this graph corresponds to those on Figures 12). The behaviour observed can be summarised as follows:

(i) All pipes show a high initial rate of heave, probably due to swelling upon access to water in the basins. The higher swelling rates in pipes D2 and D3 relative to D1 reflect their lower initial moisture contents (as shown in Figure 8) and greater capacity to draw in water. The same phenomenon was also observed in similar experiments reported by Taylor (2015). After approximately 70 days, the rates slow significantly and become steady thereafter in all cases.

(ii) Replicates D2 and D3, both located in the same open laboratory environment, exhibit very similar heave responses as found in other pipe experiments (McKeon 2015).

(iii) The curve for D1 is notably smoother than the others, probably on account of its constant temperature environment. It is interesting to note that while the curves are roughly parallel up to approximately day 500, pipe D1 experienced a period of reduced heave compared to the other pipes for approximately 150 days thereafter. The relative humidity values in the temperature-controlled room (relevant to D1 only), also plotted in Figure 13, may provide an explanation; the reduced rates may be a response to an extended period at relatively low relative humidity values. The rate accelerates again once relative humidity values increase.

Normalised heave rates are calculated as 0.0014 mm/mm/yr for D1 and 0.0016 mm/mm/yr for D2/D3 over the 470 day period for which no imposed load was applied to the Foundation Model. The corresponding rate for the Foundation model is also included in Figure 14 for comparison. In spite of the 3.4 kPa loading from the slab and sand, the foundation model heave rate was approximately 35% greater than that for D2 and D3. This may be due to unequal influences of friction at the model interfaces; while the pipe is smoother than the bitumen-coated blocks, the relative influence on the pipe walls on heave (pipe aspect ratio: height/diameter = 2.18) was greater than that of the foundation model walls (model aspect ratio: height/width = 0.36). In the foundation model, wall friction may have had a relatively smaller effect on the body of expanding fill. Given that the model aspect ratio was not very different from that in a geotechnical engineering oedometer test (height/diameter = 0.25), it is believed that the model was essentially behaving in or close to a 1-D condition, in which case the data reported herein could be considered relevant to full-width foundations.

4.4 Pressure cells

The interpretation of the pressure cells is not straight-forward, as there appears to be a number of mechanisms occurring in parallel: arching, slab restraint/compliance and thermal expansion. The responses of PC1, PC2 and PC3 over the first 20 days are shown in Figure 14; this graph is annotated with the lettering used in Section 2.1 to identify the key stages of foundation model construction. The cell responses over the entire monitoring period are shown in Figure 15(a), with pressures zeroed at day 45 presented in Figure 15(b).

(i) Arching

Arching is a phenomenon which arises in certain geotechnical engineering problems, where there is a difference in stiffness between an installed structure and the surrounding ground. The installed structure is normally stiffer than the surrounding ground, giving rise to an arching mechanism which draws additional load onto the structure. Arching can occur in tunnels, retaining walls, buried pipelines in soft ground and pile-supported embankments. Cells embedded in the ground to measure earth pressures are also susceptible to arch development, as recognised by Dunnicliff (1993) and others.

It is clear from Figure 14 that by day 7, cells PC2 and PC3 had registered pressure increases which were greater than what might expected from the geostatic stresses acting on the cells alone, i.e. ≈7.0 kPa for PC2 and ≈3.4 kPa for PC3 (significant stresses due to fill expansion will not have developed in this short time). These elevated pressures are consistent with the occurrence of arching. In this regard, it is possible that there was some interaction between PC2 and PC3 in the vertical direction. Some relaxation in these pressures occurs from day 7 onwards. This behaviour is not observed in PC1, as expected given its position along the side wall. The fact that this cell registers very little horizontal stress early in the experiment is also confirmation that the fill adjacent to the wall is carrying very little vertical load due to arch formation.

Figures 15(a) and 15(b) show that relaxation of the early arching which occurred may have taken a considerable length of time - of the order of 300 days for PC2. In parallel with the relaxation noted in PC2, PC1 gradually attracts stress, also plateauing at around 300 days also. Relaxation in PC3 is not as obvious, possibly due to the slab restraint issue discussed in (ii) occurring in parallel. It is interesting to note that the 3.4 kPa increment imposed at day 520 induced increases in pressure in PC2 and PC3 much more in keeping with the imposed stress, which suggests that no further arching is occurring at this time. Pressures in PC2 and PC3 (particularly the former) remained relatively stable thereafter.

(ii) Slab restraint

From a literature review, Maher and Gray (2014) have associated pressures in the range of 28-600 kPa with the expansion process, although these have been estimated rather than measured directly. However, the pressures in each case will be a function of the freedom with which the fill can expand,

and this interaction has not received much discussion in the literature. There is evidence of ‘compliance’ between the movement of the slab and pressures generated in this study, especially for PC3 located near the underside of the slab. For example, the period of low heave up to day 160 corresponded to increasing pressures captured by PC3, a relatively greater heave rate from days 160-300 corresponded to reducing pressures, and a reduced heave rate from days 300-520 corresponded to relatively constant pressures. In general, the relatively low pressures observed over 27-month course of the experiment are compatible with the steady uplift of a relatively unrestrained slab over this period.

(iii) Temperature

The local fluctuations in pressure identifiable in Figure 15 mirrored the temperature variations presented in Figure 10. While the pressure cells were not temperature-compensated, calibrations carried out in a similar environment (embedded in fill) indicated a pressure-sensitivity to temperature of 0.25 kPa/^{0}C (McKeon 2015), consistent with that quoted by the manufacturer based on calibrations in a heated water bath. This correction has been applied to the data in Figures 14 and 15, so the fluctuations cannot be attributed to thermal effects within the cells themselves. Given that McCabe *et al.* (2015) did not identify an influence of temperature upon the rate of expansion (in the range 10^{0}C - 20^{0}C), it is concluded that these local variations are due to thermal expansion of the materials within the Foundation Model. Cell PC2 was less sensitive to these effects, which may be due to compensating effects of its two active sides.

Once the above factors are considered and with the long-term pressures in mind, it appears likely that the fill has experienced pressures at or slightly above geostatic values, but these are relatively small in light of the range quoted by Maher and Gray (2014), due to the ability of the slab in this case to displace upwards relatively freely.

4.5 Implications for practice

A key implication of this experimental investigation is that it enables an estimate to be made of the likely duration to manifestation of damage arising from pyritiferous heave. This information is relevant to:

(i) homeowners with houses founded on fill of unknown composition, wondering if the window for pyrite-induced damage has passed, and

(ii) other interested parties assessing the type and extent of damage in relation to the time since construction.

The National House Building Council (NHBC) in the U.K. allows a maximum differential movement of 4mm per metre for floors up to 6m in width. In developing IS 398 (NSAI 2013), the threshold for damage has been adopted as 5mm differential movement over 1m across a floor slab.

The average fill thickness used in practice is adopted herein as 500mm. The rates inferred for the fill material used in this study can be scaled up linearly from the 400mm thickness used in the Foundation Model experiment to 500mm, considered valid based on the work of Sutton *et al.* (2013). Assuming that the same rates are applicable beyond the 27-month period of this study, values for 500mm thickness of fill are 1.05 mm/year (floor slab only) and 0.40 mm/year (floor slab plus 3.4 kPa imposed loading). In the 'floor slab only' case, the inferred time to 5mm uplift is 4.8 years. Using the two rates quoted above and assuming that linear interpretation between them is valid, the estimated time to 5mm uplift for a floor slab carrying 1.5 kPa imposed loading (i.e. the live load requirement under I.S. EN 1991-1-1:2002) is 6.6 years. These times should only be considered relevant to the material investigated (at laboratory temperatures) in the NUI Galway Foundation Model and it is assumed that the rates would remain relatively steady given ample availability of water. Further research is required to ascertain appropriate heave rates for fill of alternative lithologies (such as different mudstone/limestone proportions and TS values).

5. Conclusions

In this paper, the expansion of pyritiferous fill has been investigated using a larger volume of material and more true-to-life boundary conditions than have been considered heretofore. Over a period of 27 months, the movement of a concrete slab (with and without an imposed load) arising from the expansion of 400mm thickness of fill has been monitored. The experiments were conducted at laboratory temperatures (between 18^0C and 25^0C) and the reactions have been fuelled by the moisture present in the foundation system at the outset of the experiment only, without supplementary external water supply.

The following conclusions can be drawn from the study:

(i) Heave rates of 0.0021 mm/mm/yr (with load-free slab) and 0.0008 mm/mm/yr (with slab loaded to 3.4 kPa) were recorded. The former value is approximately 35% greater than those measured in pipe experiments under the same conditions. The difference may be due to the relative effects of wall friction between the two different geometries. It is believed that the conditions represented in the foundation model are at or close to 1-D and therefore the heave rates are representative of full-width foundations.

(ii) The heave in this experiment was sustained by the natural moisture content of the fill and that available from a very thin layer of boulder clay only. It is probable that rates quoted in (i) could be sustained for many years in the field, given the ready access to water from a much greater thickness of underlying foundation soil.

(iii) Relatively small pressures have been recorded within the fill, consistent with the free movement of an unrestrained slab. The relationship between heave and fill pressures is likely to be different for a restrained slab, with differential expansion more likely to cause damage than the uniform expansion observed in this study.

(iv) The rate quoted in (i) can be used to estimate the duration required to reach an appropriate heave threshold for this material (TS = 2.0 and mudstone content = 71%); further investigation is required to determine equivalent heave rates for fill materials with alternative lithologies. While the compaction density used in the Foundation Model is typical of what is used in practice; previous research at NUI Galway has indicated that the greater heave rates and/or earlier onset of heave might be expected at higher densities.

6. Acknowledgements

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Appendix A: Equations detailing the process of oxidation of pyrite in weathering environments and the formation of gypsum from weathering products and calcite. Some of these processes involve bacteria.

$$FeS_2 + H_2O + 3.5O_2 \rightarrow FeSO_4 + H_2SO_4 \quad [1]$$

$$2FeSO_4 + 0.5O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O \quad [2]$$

$$Fe_2(SO_4)_3 + FeS_2 \rightarrow 3FeSO_4 + 2S \quad [3]$$

$$S + 1.5O_2 + H_2O \rightarrow H_2SO_4 \quad [4]$$

$$FeS_2 + 3.75O_2 + 3.5\ H_2O \rightarrow Fe(OH)_3 + 2H_2SO_4 \quad [5]$$

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 2H_2O + CO_2 \quad [6]$$

AS (SO_4) (%)	WS (mg/L SO_4) (%)	TS (S) (%)	**OS (S) (%)**	**Original Pyrite (%)**	**Existing Pyrite (%)**	**Oxidised Pyrite (%)**	**% of Original Pyrite Oxidised**
4.18	1886	2.00	**0.61**	**3.74**	**1.13**	**2.61**	**69.7**

AS = Acid Soluble Sulphate

WS = Water Soluble Sulphate

TS = Total Sulphur

OS = Oxidisable Sulphur

Table 1: Chemical Test Results

Figure 1a: NUI Galway Pyrite Foundation Model

Figure 1b: NUI Galway Pyrite Foundation Model with 3.4kPa imposed load

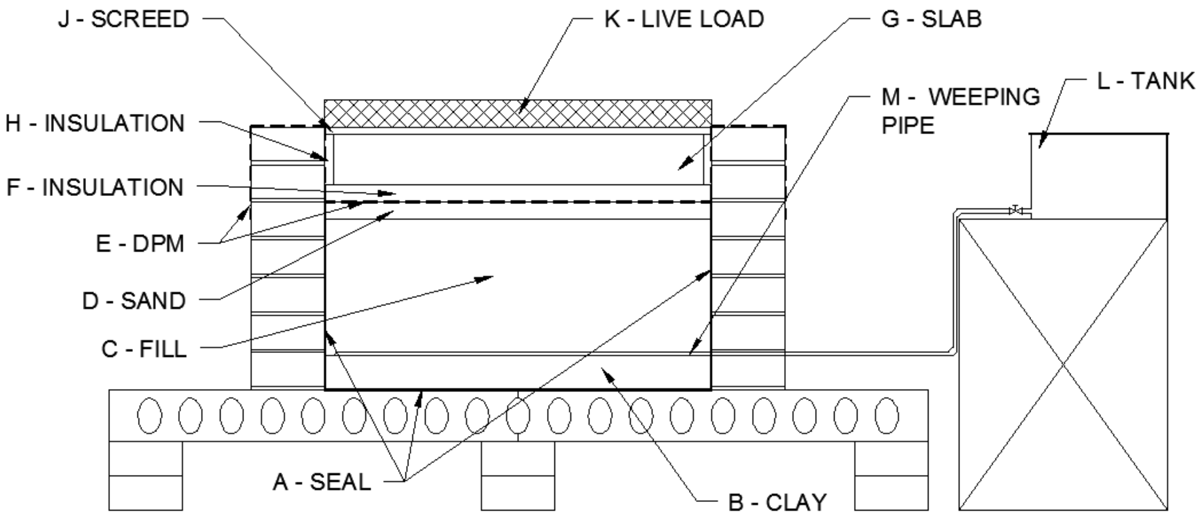

Figure 2: Schematic of NUI Galway Pyrite Foundation Model

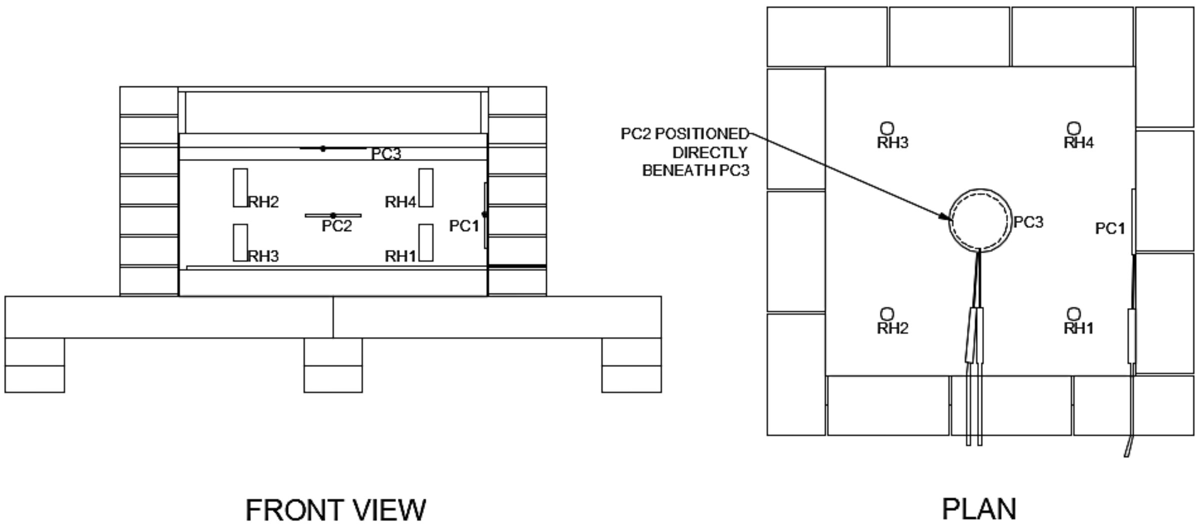

Figure 3a: Front and plan views of NUI Galway Pyrite Foundation Model showing locations of RH1-RH4 and PC1-PC3

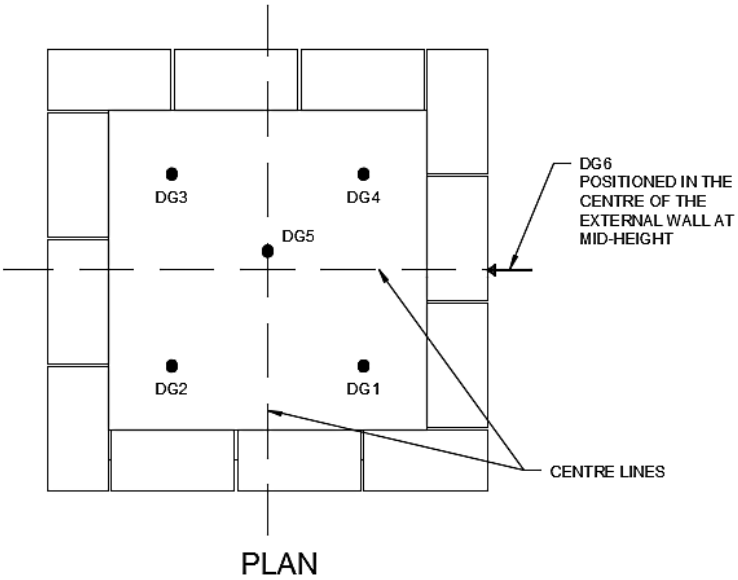

Figure 3b: Plan view of NUI Galway Pyrite Foundation Model showing locations of DG1-DG6

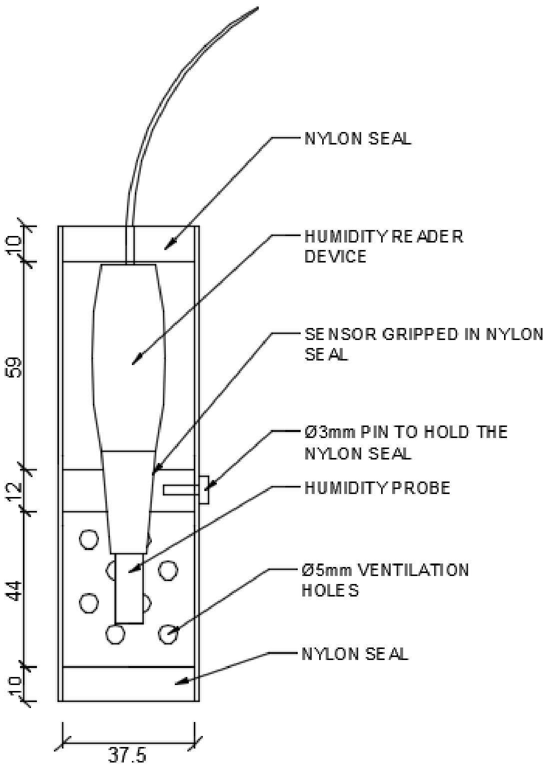

Figure 4: Relative humidity probe housing

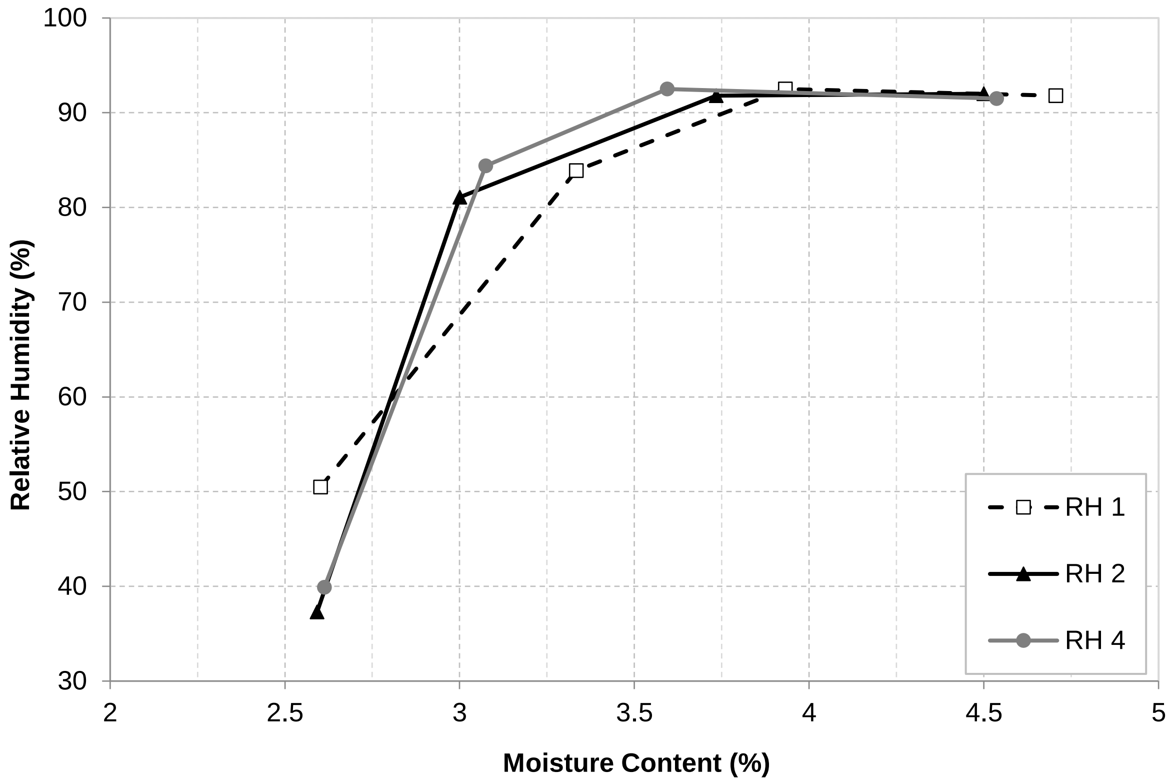

Figure 5: Relative humidity probe calibrations

Figure 6: Reference pipe experiments (D2 and D3)

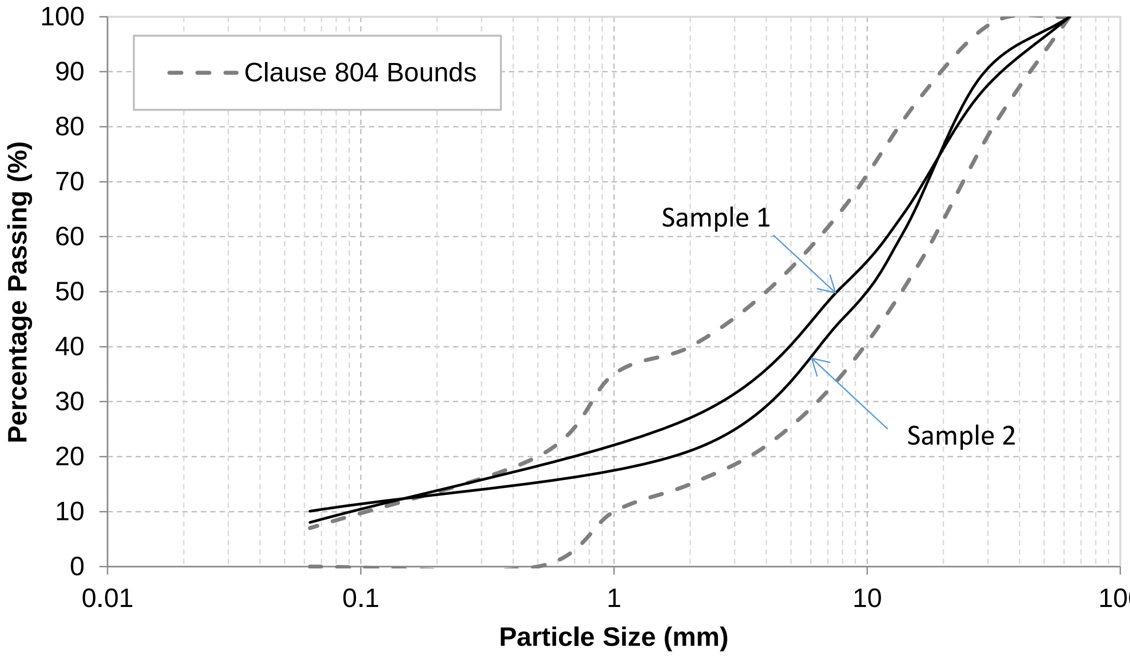

Figure 7: Grading of samples of the fill used

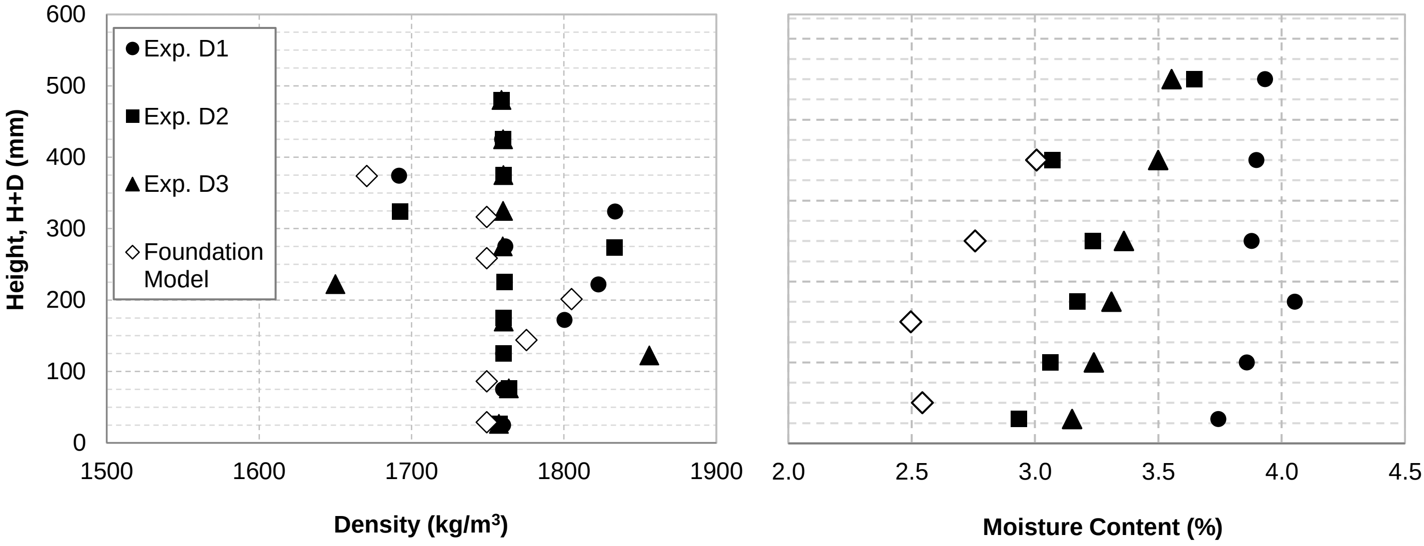

Figure 8: Initial density and moisture content profiles in Foundation Model and pipes

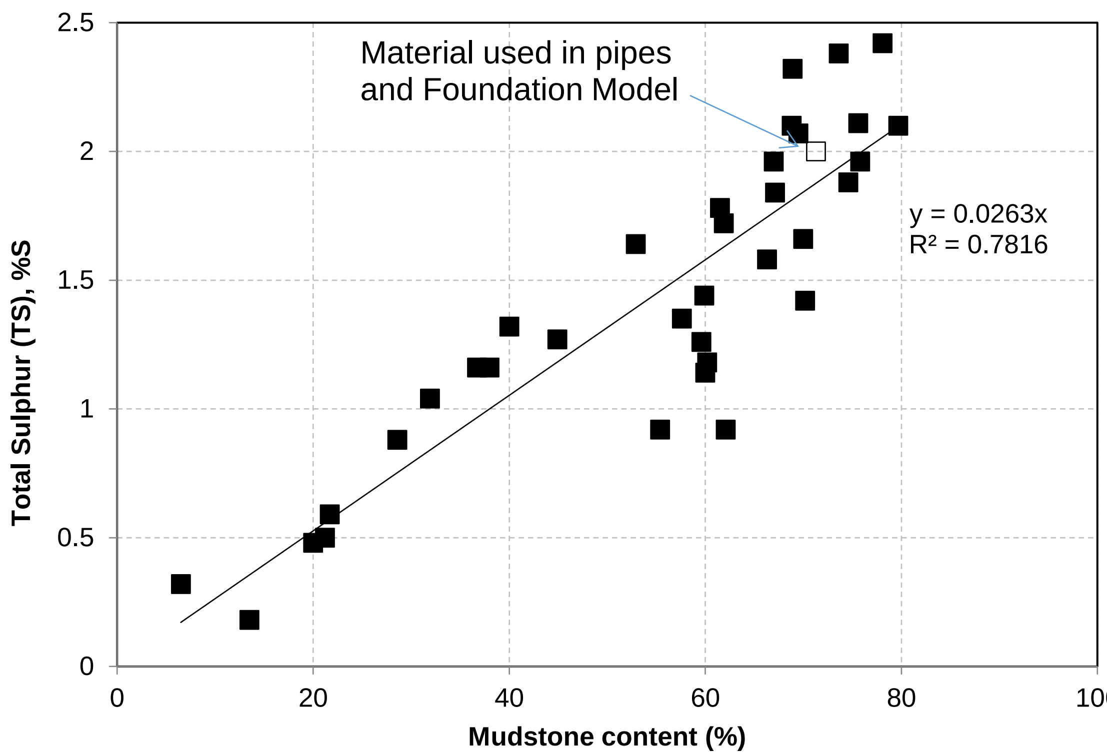

Figure 9: Total Sulphur against Mudstone content for samples in the development tested by Sandberg LLP laboratories.

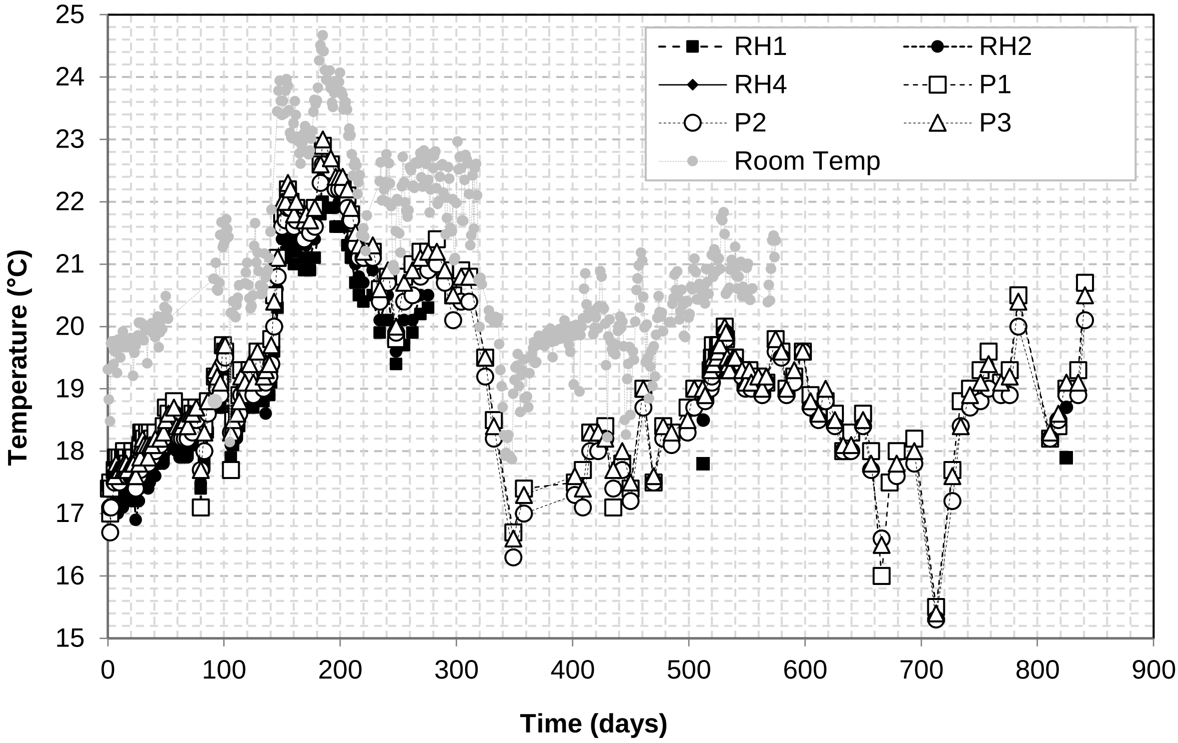

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Figure 10: Temperature measurements: room, pressure cells and RH sensors

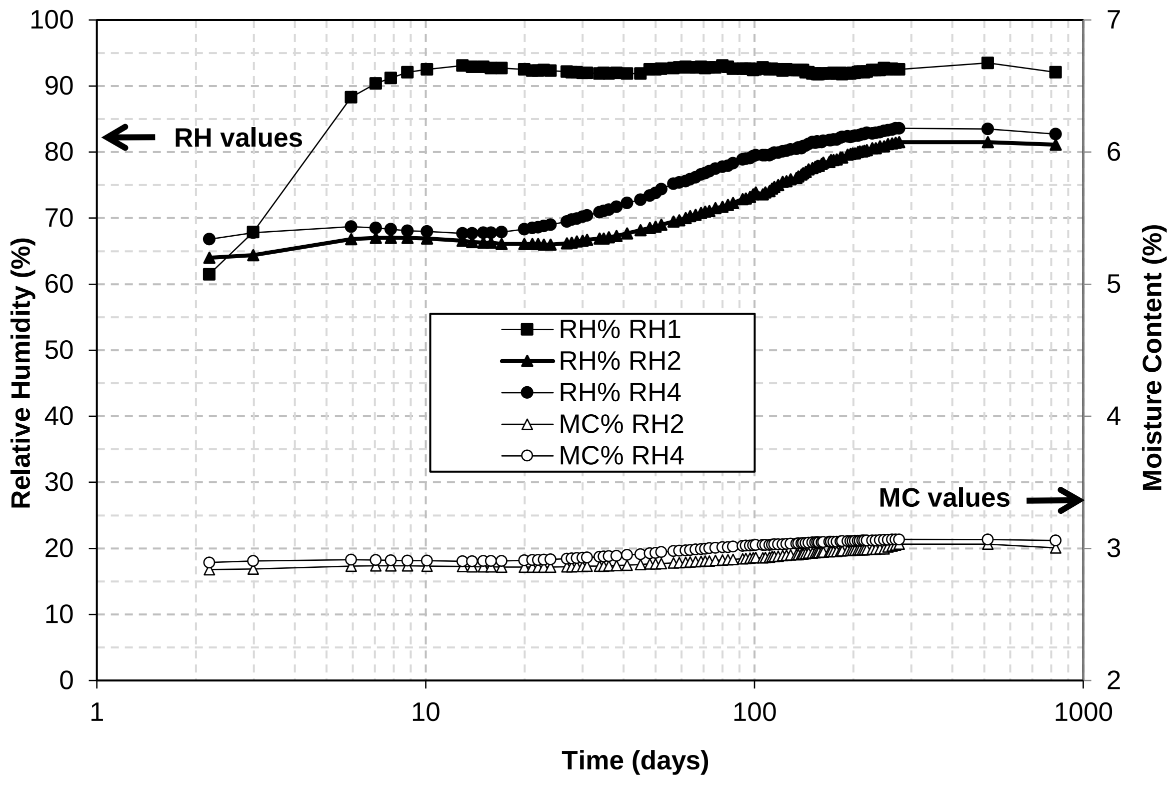

Figure 11: Variation of relative humidity and inferred moisture content with time

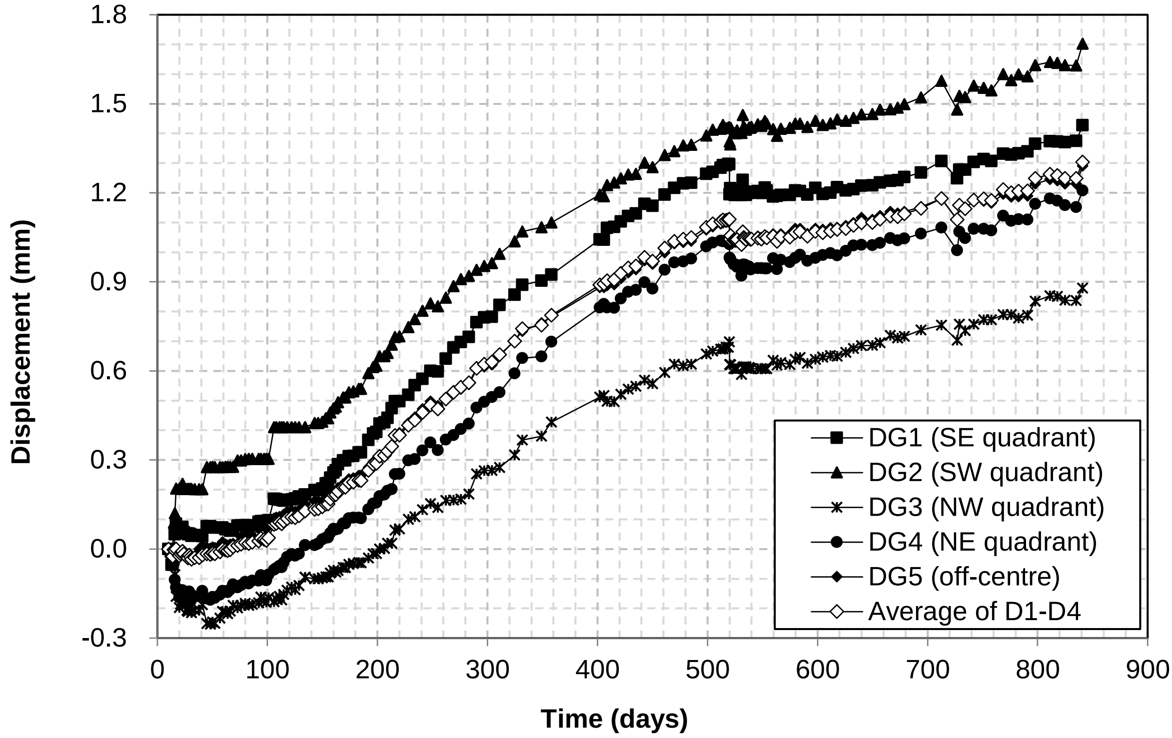

Figure 12a: Heave displacement versus time

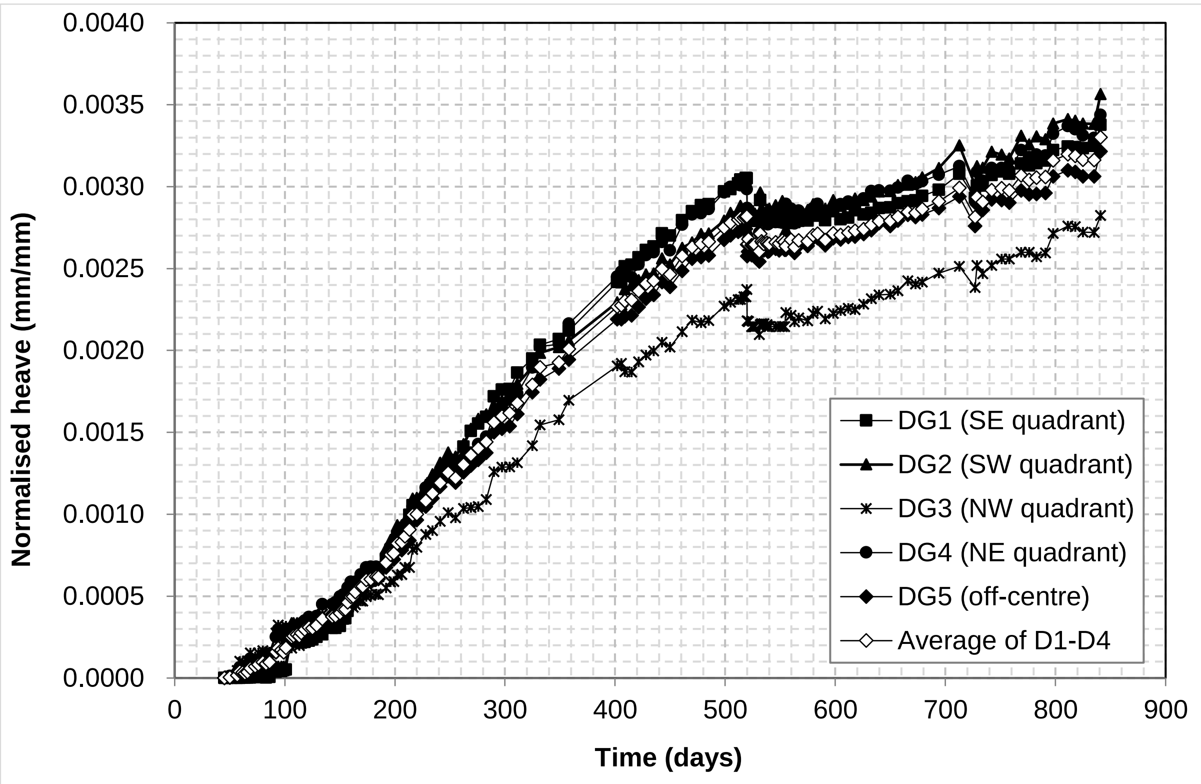

Figure 12b: Normalised heave displacement (zeroed at day 45) versus time

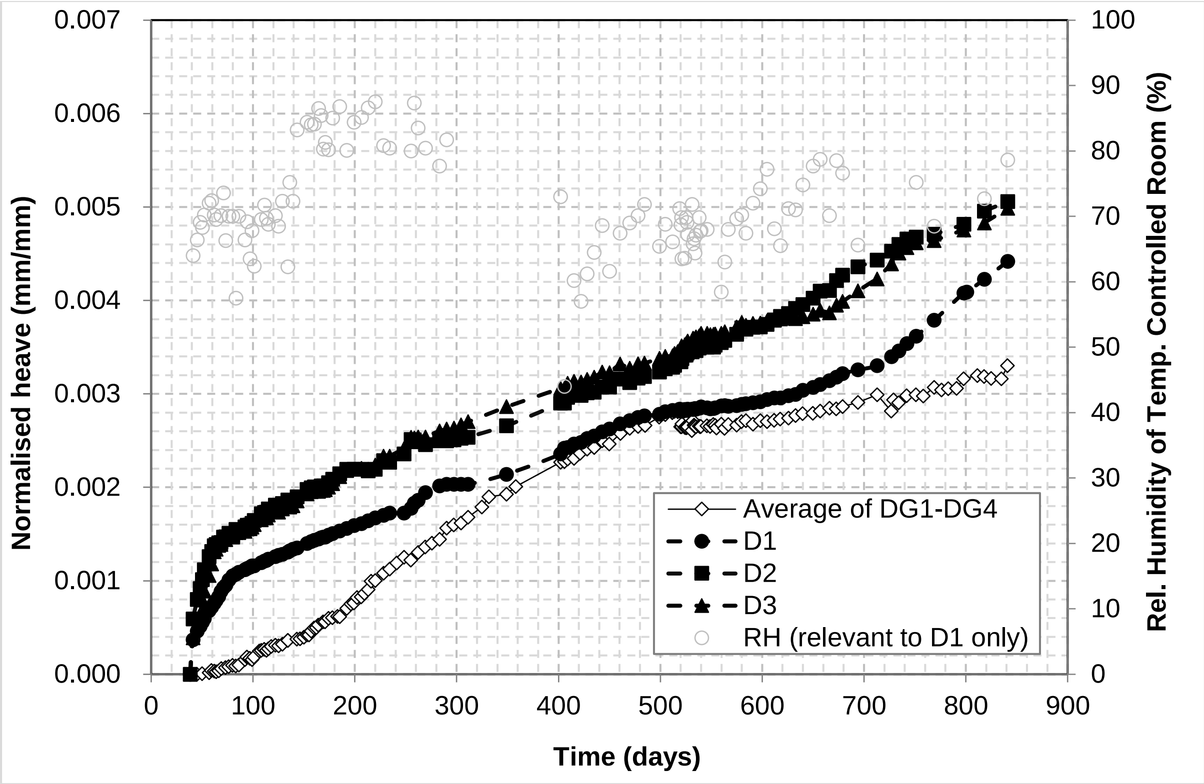

Figure 13: Normalised heave of Foundation Model and D1-D3 versus time since the start of the Foundation Model testing

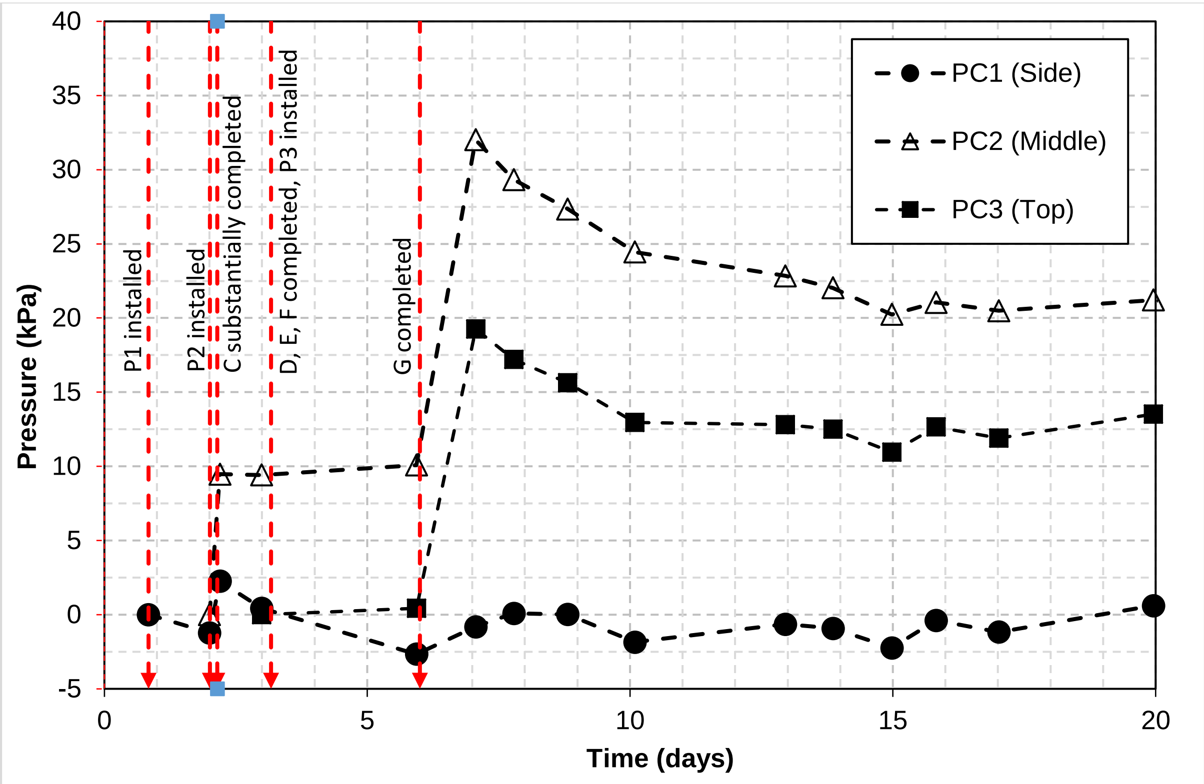

Figure 14: Pressure versus time (first 20 days)

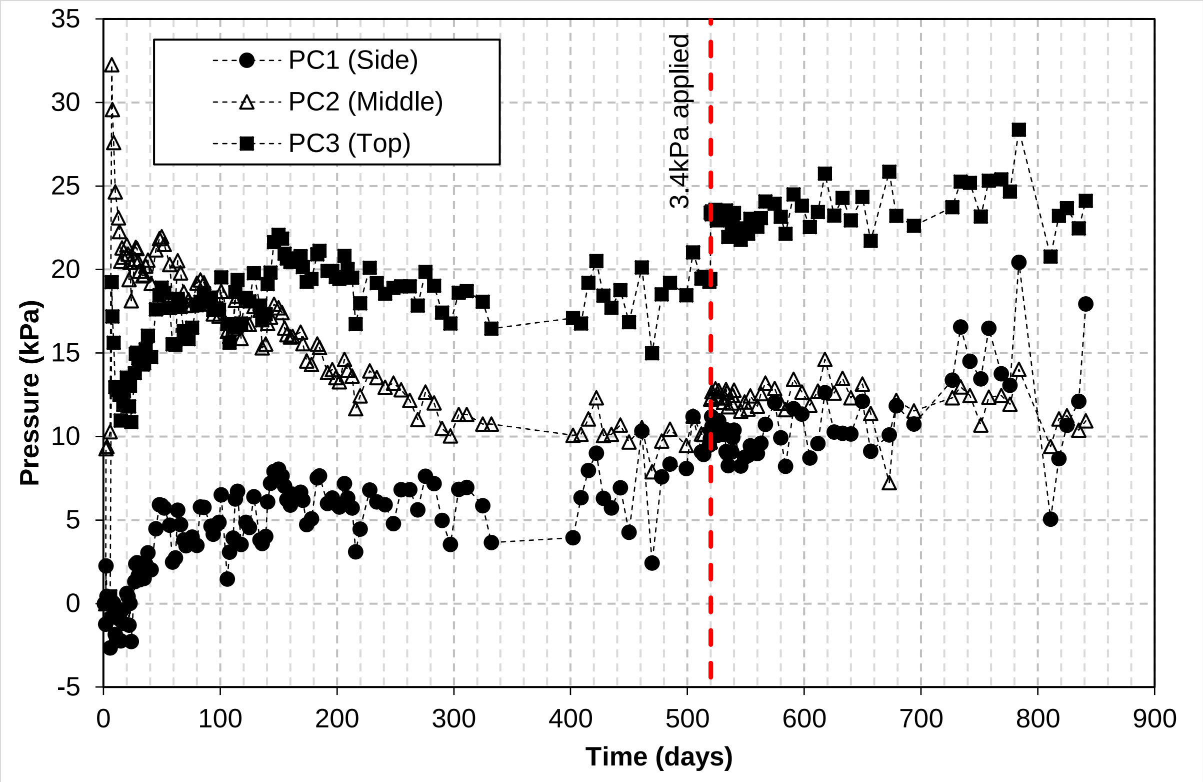

Figure 15a: Pressure versus time

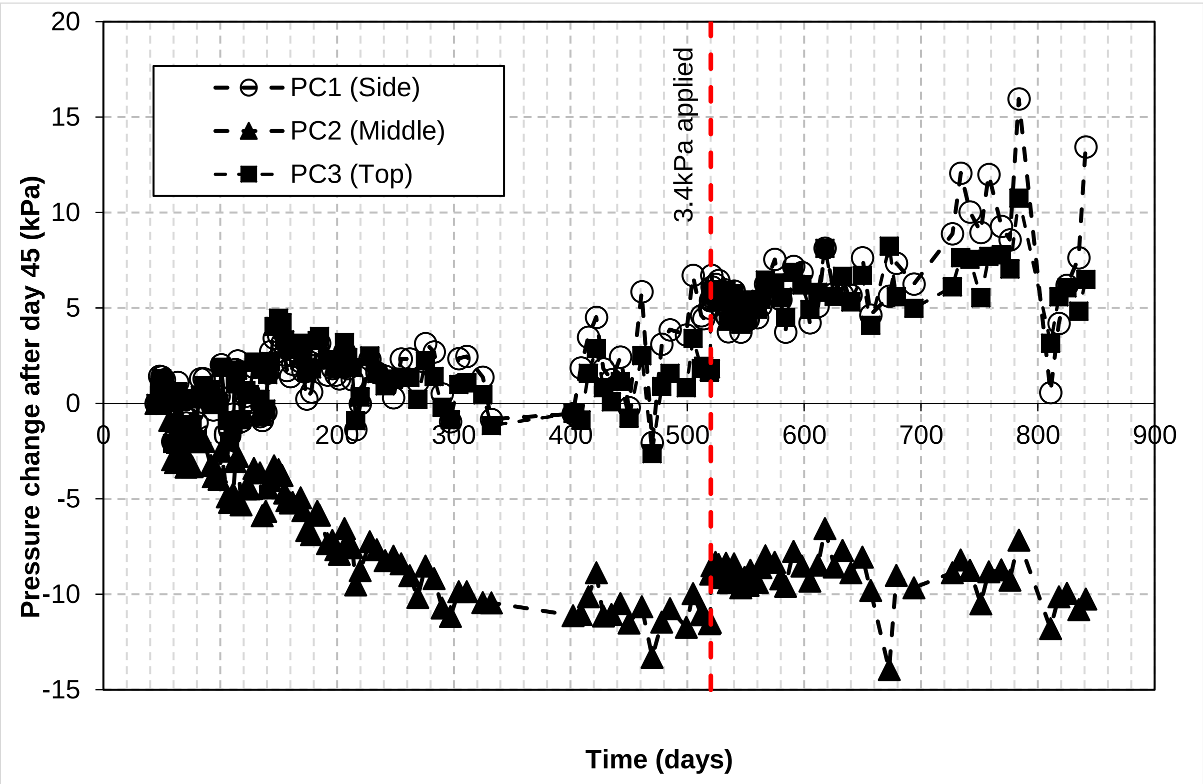

Figure 15b: Pressure (zeroed at day 45) versus time