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|-----------------------------|---|
| Title | Heave-ho! A laboratory model of an underfloor environment incorporating pyritiferous fill |
| Author(s) | McKeon, E.P.; McCabe, Bryan A.; Sexton, Brian G.; Cavalcante, M.; Ibanez-Valle, J.L.; O'Connell, A.M. |
| Publication Date | 2016 |
| Publication Information | McKeon, E.P., McCabe, B.A., Sexton, B.G., Cavalcante, M., Ibanez-Valle, J.L., O'Connell, A.M. (2016) Heave-ho! A laboratory model of an underfloor environment incorporating pyritiferous fill Proceedings of Civil Engineering Research in Ireland (CERI 2016), Galway |
| Publisher | NUI Galway |
| Link to publisher's version | https://doi.org/10.13025/S8F30J |
| Item record | http://hdl.handle.net/10379/6322 |
| DOI | http://dx.doi.org/10.13025/S8F30J |

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Heave-ho! A laboratory model of an underfloor environment incorporating pyritiferous fill

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ABSTRACT: Damage to domestic dwellings in the greater Dublin area of Ireland caused by the expansion of underfloor fill material containing pyrite has become a high-profile national problem in recent years. In this paper, a novel experiment is described in which the succession of underfloor materials, with vertical dimensions at full scale, is reproduced. The study has enabled the amount/rate of expansion and pressures generated due to the expansion of the pyritiferous fill, with and without imposed loading on the concrete slab, to be ascertained over a period of 800 days. The rates of expansion are relatively consistent with those recorded from reference pipe experiments. These data form an important frame of reference for anticipating the time at which damage might begin to manifest itself in domestic dwellings.

KEY WORDS: pyrite; mudstone; expansion.

1 INTRODUCTION

The rapid economic growth experienced by the Republic of Ireland from the mid-1990s was influenced significantly by a buoyant construction industry. House-building was a major contributor, with the number of units completed in a calendar year peaking at 88,188 in 2006, compared to 30,575 in 1995 [1]. Tuohy *et al.* [2], 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 used in house foundations in the east of Ireland contained pyrite, a naturally-occurring mineral that oxidises to form products including sulphuric acid. Sulphuric acid reacts with calcite (another common mineral constituent of fill materials) to generate gypsum which can give rise to an increased fill volume compared to the original pyrite and calcite. The reaction process is detailed in Reid *et al.* [3]. Expansion of pyritiferous 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. Czerewko and Cripps [4] provide a useful schematic of the process.

Experimental research has been carried out at NUI Galway since 2010 to identify the factors upon which pyritiferous expansion depends [5-7]. 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 229mm in diameter standing vertically in plastic basins with varied depths of water in the basins. Vertical movement of the fill was recorded using a dial gauge mounted on an independent frame. 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.

Sutton *et al.* [5] prepared ten such pipes with constant density (approx. 2000 kg/m³) using a single fill source and varied the fill height (500 mm, 750 mm and 1000 mm) and the depth of water, i.e. submerged depth (30mm and 60mm). The pipes were situated in an unheated laboratory, so ambient temperatures closely tracked seasonal changes, generally increasing from 4°C to 15°C over 6 months. Significant expansion was manifest (which has not always been the case in unaccelerated studies elsewhere [e.g. 8]) and changes in the pH of the water in the basins were consistent with the generation of sulphuric acid. The magnitude of heave was proportional to the fill depth. However, the submerged depth was found to have little effect.

Using fill from a different source, McCabe *et al.* [6] reported on six further tests using the same apparatus with constant fill heights (500 mm), varied densities (nominally 1800 kg/m³, 2000 kg/m³ and 2200 kg/m³) and varied water depths (10 mm and 30 mm), situated in a temperature-controlled room with hold periods at 10°C, 15°C and 20°C over the duration of testing. Earlier heave onset times and/or greater heave magnitudes were observed in higher density fill. There was no long-term effect of temperature on the rate of heave over the temperature range considered once the effects of thermal expansion of the entire experimental system were accounted for.

From heave rates measured at NUI Galway and those reported by Maher *et al.* [9], McKeon [7] inferred that the rate of heave may be influenced by the proportion of mudstone in the fill material. This relationship is currently under systematic investigation at NUI Galway.

In this paper, a novel 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 block wall of the model represents the rising walls and encloses a vertical succession of materials from the *in situ* soil to the concrete floor slab, including some pyritiferous fill material. The heave of the slab was monitored, in addition to the relative humidity and pressure at points within the body of fill. A load was imposed on the slab after 17 months and the tests have been in progress for a period of 26 months at the time of writing. Three pipe experiments (of the type described in [5-7]), using fill from the same batch incorporated in the foundation model, were carried out in parallel for reference.

2 EXPERIMENTAL ARRANGEMENTS

2.1 Foundation Model Materials

The NUI Galway Pyrite Foundation Model (FM) comprises a masonry box structure with internal dimensions of 1.125 m × 1.125 m × 0.770 m (Figure 1). The blockwork walls were constructed on two adjacent precast concrete slabs, raised off the ground. The walls consist of seven courses of standard 4-in (100 mm) blocks built on the flat face giving a 210 mm-thick wall consistent with conventional rising wall construction in Ireland. The vertical succession of materials/finishes A-K and M is shown in Figure 2.



Figure 1. NUI Galway Pyrite Foundation Model, including imposed load of 3.4 kPa (inset: pipe experiments D2 and D3).

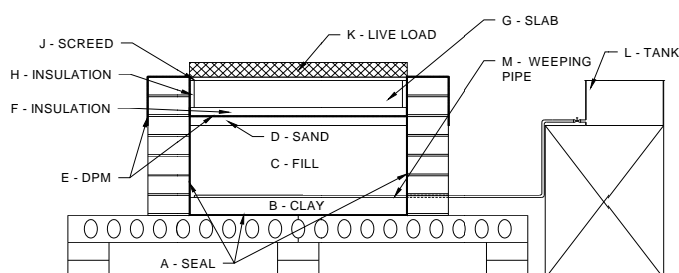


Figure 2. Section through NUI Galway Pyrite Foundation Model.

A: Bituminous seal:

The bituminous seal was applied internally to the base and to the sides up to the level of the underside of the concrete slab (i.e. 600mm above the base) with a view to inhibiting any moisture escape which would induce drying of the fill.

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 construction of the foundation model was found to be approximately 19%, while values of plastic limit and liquid limit were established as 17% and 35% respectively. These results are consistent with those of Upper Brown Dublin Boulder Clay as reported by Menkiti and Long [10]. The clay was spread evenly on the base of the model and compacted in one 100mm layer to approximately 2000 kg/m³ using a bespoke 15kg tamper.

C: Pyritiferous mudstone fill:

Fill thicknesses in practice are typically 400-600 mm; 400 mm was adopted for this experiment. The target density of the fill was approximately 1800 kg/m³, in keeping with values back-calculated by 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 layers, each 55 mm – 60 mm deep, taking care that few fill particles were crushed during the compaction process. In Figure 3, the density achieved in each layer in the foundation model is plotted as a function of the height from the bottom of the fill to the midpoint of each layer (hollow symbols). Moisture contents (determined at 105°C) of samples taken 50 mm, 150 mm, 250 mm and 350 mm from the bottom of the fill are represented in Figure 4.

D: Blinding sand:

A 50mm thickness of blinding sand was laid at a density of 1600kg/m³. Given that the radon gas extraction system required by Irish Building Regulations would allow air to circulate to underfloor fill in practice, 5 no. 20mm dia. holes were drilled in each of the four side walls at a level corresponding to mid-depth in the sand. This facilitates the oxidation process through access to fresh air.

E: 1200 gauge Damp Proof Membrane (DPM):

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

F: High density insulation:

Kingspan Kooltherm K3 Floorboard, 50mm 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 1.075m ×

1.075m in plan by 150mm in thickness. Elements D, F and G imposed a combined stress of 3.4kPa on the fill.

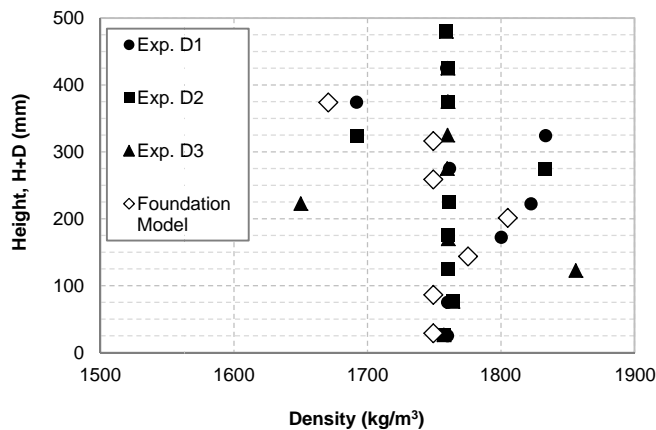


Figure 3. Initial density v height for FM and D1-D3.

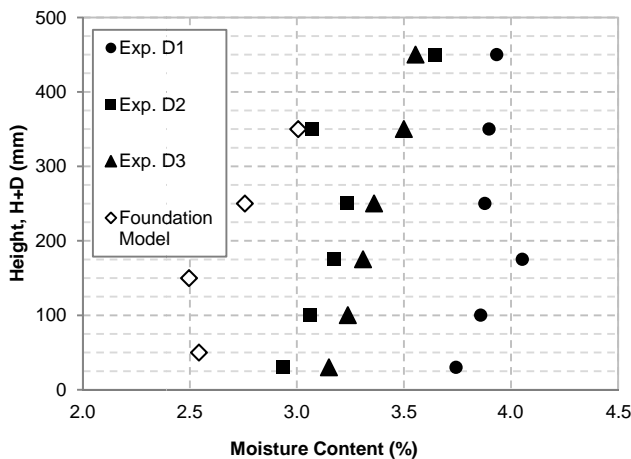


Figure 4. Initial moisture content v height for FM and D1-D3.

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:

I.S. EN 1991-1-1:2002 [11] requires slabs in domestic dwellings to be designed for a live load of 1.5kPa. An external load was imposed approximately 17 months after commencement of the experiment using concrete blocks (soap bars) of nominal dimensions 95mm × 95mm × 445mm. A total of 50 soap bars (some split into two) provided an average loading of approximately 3.4kPa 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 to induce a clear response. As can be seen from Figure 1, the positions of the soap bars were dictated by the positions of both the dial gauges and the requirement of an unobstructed line-of-sight to them; the plan area coverage is approximately 71%.

A **water tank (L)** was also provided outside the model with its base 400mm above the top of the clay layer, which can be connected to a '**weeping pipe**' (**M**) irrigation facility at the interface between the clay and fill. This was intended to provide additional water to the fill which may be available from a thicker clay layer in the field. However, since the expansion rate did not show signs of abating after 800 days, this irrigation facility was not utilised.

2.2 Relative Humidity Probes

Relative humidity probes RH1-RH4 were used to assess the moisture content of the fill at two levels. All sensors were located 227mm from the side walls. Two probes RH1 and RH3 were positioned in diagonally-opposite locations 100 mm above the bottom of the fill while the other two diagonals were occupied by sensors RH2 and RH4, 300 mm above the bottom of the fill. The fill surrounding the probe housing was sieved and only particles larger than 5mm were placed within 50 mm. This ensured that little deleterious matter passed through the 5 mm dia. holes in the housing reducing the chance of probe clogging or damage. Each relative humidity cable was sealed in a rubber covering to avoid damage.

Small containers of fill were used to develop calibrations between relative humidity and moisture content for RH1-RH4 prior to their incorporation within the foundation model. The relationships were non-linear but repeatable, in keeping with research showing that the relationship between the relative humidity of an air pocket in a concrete cube sample and the moisture content was non-linear [12]. However, the relationships were only valid up to a moisture content of approximately 4%, after which the relative humidity remained at 90-95% irrespective of moisture content. Therefore inference of moisture content from the sensors would only be meaningful if the moisture content remained below 4%. A similar experience of limited useful range of humidity sensors has been reported at the University of Sheffield [13]. Each of the probes RH1-RH4 also recorded temperature.

2.3 Pressure Cells

Two single-sided and one double-sided circular vibrating wire pressure cells (supplied by ITM Soil Ltd., 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 range of all the pressure cells used was 0-1 MPa in allowance for the possible development of high stresses (damage to the Golder Swell Test [9] was calculated to have required a pressure of 600 kPa). Each cell also incorporated a thermistor.

One single-sided pressure cell (PC1) was placed vertically on the middle of the block wall, with active side facing the fill. 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 vertically above PC2 with active side facing down at the interface between the sand layer and insulation. Only particles passing the 5 mm sieve were placed within 25 mm of the cells in keeping with the manufacturer's instructions. 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. Each pressure cell also measured temperature.

2.4 Dial Gauges

The movement of the concrete slab was monitored by dial gauges, one in the centre of each quadrant of the slab (DG1-DG4) and a fifth near the centrepoint of the slab (DG5). 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 walls and slab of the foundation model.

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

2.5 Reference Pipe Experiments

In order to ascertain the relative performances of the foundation model and the pipe apparatus [5-7], 3 no. pipe experiments D1 to D3 were established using fill derived from the same batch and compacted to approximately the same average density as the foundation model. The first expansion readings from these pipes were taken 28 days after the first expansion readings from the foundation model. Test D1 was subject to a temperature of 20°C (for the vast majority of the testing period) in a temperature-controlled room. Replicate tests D2 and D3 were located in immediate proximity to the foundation model in the open laboratory (inset to Figure 1); and were therefore exposed to the same temperature and humidity variations. Variations of initial density and moisture content over the 500mm depth of fill are also shown in Figure 3 and 4 respectively (solid symbols), where they can be compared to those of the foundation model.

3 PYRITIFEROUS MUDSTONE FILL PROPERTIES

3.1 Introduction

The fill sample used in the foundation model and in the reference pipe tests D1-D3 was originally quarried in 2005. In 2013, it was extracted from the foundation of a house in Co. Dublin undergoing remediation for damage due to pyritiferous heave. Geological tests were carried out in 2012 by Sandberg LLP Laboratories, London, on samples of fill taken from the same house prior to the remediation process.

3.2 Moisture Content, Grading and Lithology

A single moisture content value of 4.6% (air dried at 38°C) was reported in 2012 [14], suggesting that the material may have dried slightly before the experiments were performed (see Figure 3). The fill is classified as a sandy GRAVEL and the grading largely conforms to National Roads Authority (NRA) Clause 804 bounds. A description of the main rock types was given for the sample as part of the geological report [14]; three distinct lithologies were identified: (i) Calcareous (silty, carbonaceous) mudstone, (ii) Typically strong, argillaceous (silty, carbonaceous) limestone and (iii) Typically strong limestone (carbonaceous and non-carbonaceous). The report also stated that the surfaces of the fill particles were covered in abundant calcareous and argillaceous dust that contained altered framboidal pyrite. Gypsum crystals were present on the surface of some particles.

3.3 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.* [3]. Electron microscope and X-Ray diffraction test results for the fill used in this research are shown in Table 2.

Table 1. Chemical test results

| 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 |

Table 2. Electron Microscope and XRD test results

| Total Mudstone (%) | Total Calcareous Mudstone. (%) | Total Non-Calcareous Mudstone (%) | Mudstone with gypsum- filled cracks (%) | Total Limestone (%) | Gypsum (%) | XRD Testing | | |
|-----------------------|--------------------------------------|---|---|------------------------|---------------|---------------|----------------|---------------|
| | | | | | | Pyrite (%) | Calcite (%) | Gypsum (%) |
| 71.3 | 15.2 | 43.9 | 12.2 | 15.8 | 1.2 | 2.1 | 13 | 11 |

4 RESULTS AND DISCUSSION

4.1 Temperature in laboratory and in fill

The ambient room temperature varied in the range 18°C-25°C over the duration of the experiment. The temperatures recorded by PC1-PC3 and RH1-RH4 typically fell 1.5°C and 2°C below the recorded ambient temperature respectively. The room temperature was used to estimate the thermal expansion of the reference frame and dial gauges while the temperature measurements from within the model were used to determine the thermal expansion of the internal materials.

The coefficient of thermal expansion of the fill was assumed equal to that measured for a pyrite-free Clause 804 fill material established in two additional pipes ($15 \times 10^{-6}/^{\circ}\text{C}$) [7]. The effect of thermal expansion on the entire experimental system was found to be negligible.

4.2 Humidity in fill

RH3 failed to operate consistently once installed within the foundation model, so its results were excluded. The initial humidity readings for RH1, RH2 and RH4 taken once the foundation model was established (60-70%) indicated moisture contents that were broadly compatible with those shown for the foundation model in Figure 4. The subsequent variation with time can be summarised as follows:

- 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 upper limit of the calibration.
- 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 represent increases of the order of 0.25% from the initial values.

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

4.3 Heave

4.3.1 Foundation Model

In Figure 5, the magnitudes of heave are normalised by the fill thickness of 400mm and zeroed at the 45 day mark, before which self-weight settlement and some tilting of the slab arose. The normalised heave registered by the centre gauge shows almost identical output to the average of gauges DG1-DG4. In the absence of imposed loading, the average normalised heave rate over a 470 day period 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 0.0007 mm/mm/yr or 0.27 mm/yr (for 400mm). This reduced rate is in keeping with experience that more heavily loaded ground floor rooms such as utilities and kitchens experience lower rates of 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. Moreover, a visual inspection of the blockwork and joints showed no evidence of deterioration over time.

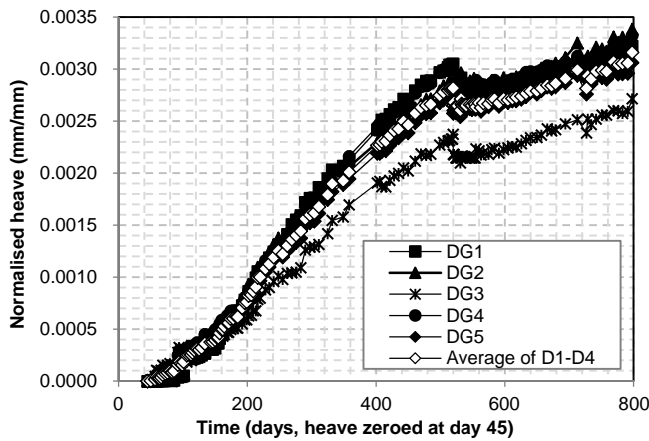


Figure 5. Normalised displacement v time for FM.

4.3.2 Pipe experiments

The movements registered by all pipes D1-D3, normalised by their fill heights of 500mm, are plotted on Figure 6 (the time origin on this graph corresponds to that on Figure 5). Replicates D2 and D3 exhibit very similar heave responses, demonstrating repeatability as found in other pipe experiments [7]. The curve for D1 is notably smoother than the others, probably on account of its constant temperature environment.

All pipes show a high initial rate of heave, which is greater for those pipes in the open laboratory. At the time of writing,

this is believed to be an ‘establishment’ effect which is a function of the experimental arrangement rather than the expansion process; the same phenomenon was also observed in expansion experiments in the University of Sheffield [15]. At approximately 70 days, the rates slow significantly and become steady thereafter in all cases, with a normalised heave rate of 0.0014 mm/mm/yr for D1 and 0.0016 mm/mm/yr for D2/D3 over a 470 day period. The average normalised heave rate for the Foundation model (prior to the imposed load) is also included in Figure 6 for comparison. In spite of the 3.4 kPa loading from the slab and sand, the foundation model heave rate is 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) is greater than that of the foundation model walls (model aspect ratio: height/width = 0.36). In the foundation model, wall friction may have a relatively smaller effect on the body of fill.

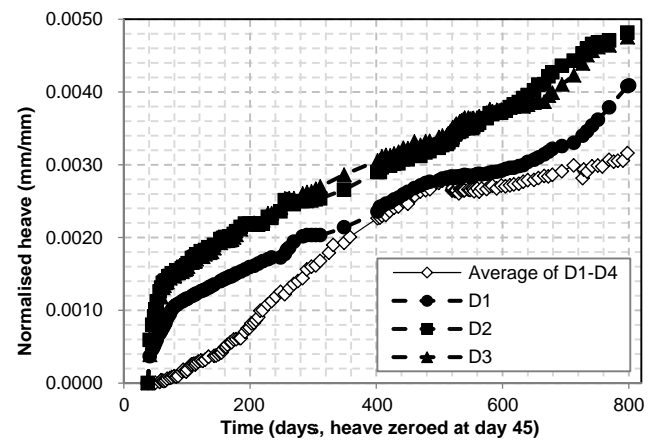


Figure 6. Normalised displacement v time for FM, D1-D3

4.4 Pressure

In Figure 7, the net pressure (zeroed at the 45 day mark to correspond with the observed heave, see Figure 5) is plotted against time. The following comments can be made about the pressure cell output over the course of the experiment:

- (i) The pressures are relatively low, consistent with an unrestrained slab that has been lifting steadily. In fact, the measured pressures are at the lower end of the 28-600 kPa range established by Maher and Gray (2014) from a literature review, although all of these have been estimated rather than measured directly. In any case, the levels of restraint of the slab will dictate the relative development of heave and fill pressures.
- (ii) The slight differences in heave rates up to 520 days identifiable in Figure 5 can be explained by subtle pressure change patterns in Figure 7, albeit the pressure changes are relatively minor. For example, the period of higher heave from days 160-300 corresponds to reducing pressures, whereas the reduced rate from days 300-520 corresponds to relatively constant pressures.
- (iii) The local fluctuations in pressure mirror the temperature variations, so therefore reflect the thermal expansion and

contraction of the materials within the Foundation Model. Cell PC2 is less sensitive to these effects, as might be expected due to compensating effects of its two active sides.

- (iv) The 3.4 kPa load applied on day 520 induced the expected step increases in PC2 and PC3 (annotated on Figure 7). The effect was less clear for PC1 as might be expected given its orientation.

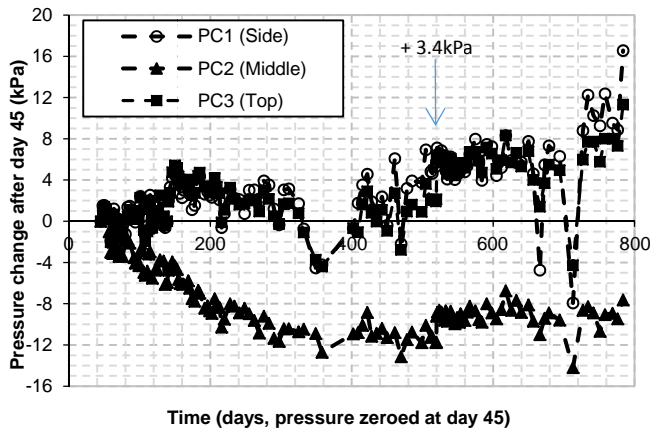


Figure 7. Net pressure v time.

4.5 Discussion

Adopting 500mm as the average fill thickness used in practice, the rates inferred for the fill material used in this study can be extrapolated from 400mm to 500mm (valid based on previous research [5]), becoming 1.05 mm/year (floor slab only) and 0.34 mm/year (floor slab plus 3.4 kPa imposed loading).

A key implication of these expansion rates is that they enable an estimate to be made of the likely duration to manifestation of damage arising from pyritiferous heave. This information is relevant to:

- homeowners with houses founded on pyrite-free fill material, wondering if the window for pyrite-induced damage has passed, and
- interested parties assessing whether damage claimed for has resulted from pyrite.

In developing IS 398 [17], the new Irish standard for pyrite, the threshold for damage has been adopted as 5mm differential movement over 1m across a floor slab. Therefore, in the 'floor slab only' case, the inferred time-to-damage is 4.8 years. Using the two rates quoted above and assuming that linear interpretation between them is valid, the estimated time-to-damage for a floor slab carrying 1.5 kPa (imposed live load requirement [11]) is 6.8 years. It should be noted that these times-to-damage should only be considered relevant to the material investigated in this research in the NUI Galway foundation model; further research is required to ascertain appropriate heave rates and times-to-damage for fill of alternative lithologies (such as different mudstone/limestone proportions and TS values).

5 CONCLUSION

In this paper, the expansion of pyritiferous fill has been investigated using a larger volume of material and more

representative experimental boundary conditions than have been considered heretofore.

Over a period of 800 days, 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 moisture content has been maintained constant and fill temperatures have varied between 16°C and 23°C. Relatively small pressures have been recorded within the fill, consistent with the free movement of the slab observed. Heave rates have been reported as 0.0021 mm/mm/yr (with load-free slab) and 0.0007 mm/mm/yr (with slab loaded to 3.4 kPa). These rates can be used to estimate the duration required for damage to occur assuming an appropriate damage threshold, such as the 5mm differential movement alluded to in IS398.

Further investigation is required to determine equivalent heave rates and times to damage for fill materials with alternative lithologies.

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