The Effect of Pyrite-Related Heave: A Structural Engineer's Perspective

Paul M. Forde

Introduction

It is well known that structures may suffer distress related to ground conditions, for example as a consequence of mining, dissolution in limestone terrain, landslips, inadequate bearing capacity etc., while seasonal shrink/swell often causes cracks to open in summer and close in winter. However, when a number of new properties in the Dublin area were found to be experiencing significant distress in 2006, none of these more common causes could explain the ongoing problem. After some early misdiagnoses, it was found that the buildings were affected by heave due to sulphate generation in the imported fill.

This chapter presents some experience of dealing with the effects on houses when sulphates developed in a pyritiferous infill placed beneath ground-bearing floor slabs.

Background to the Problem

My first introduction to the problem was on a housing development of over 400 homes in 2006. The houses had only been built in 2003/2004 yet the owners were complaining of cracks opening above door heads in internal walls. These walls had been built directly on a continuous ground-bearing floor slab rather than on individual rising walls. On inspection, the cracks appeared to be far more severe than would be expected in new properties. Subsequently, DBFL were asked to consider a number of other properties which had suffered similar damage.

Initially the problem was misdiagnosed as settlement of deep sections of fill against rising walls (Fig. 1). In the first houses, it was recommended that grout

P. M. Forde (✉)
DBFL Consulting Engineers, Dublin, Ireland
e-mail: paul.forde@dbfl.ie

A. B. Hawkins, *Implications of Pyrite Oxidation for Engineering Works*, 187
DOI: 10.1007/978-3-319-00221-7_6,

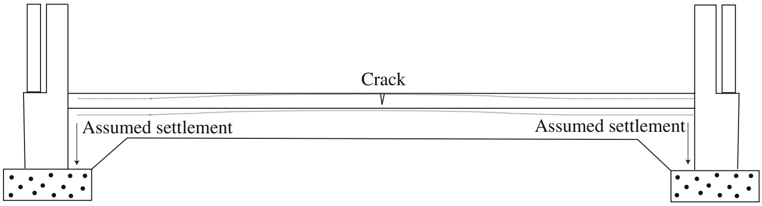


Fig. 1 Initial interpretation of cracking in the ground-bearing floor slab

should be pressure-injected into any voids in the fill. However, when cracking recurred in the same houses, it was clear that a different cause was responsible and it would be necessary to review the previous conclusions.

In late 2006 samples were taken from one of the houses and sent to Trinity College, Dublin. Following testing by Dr. Robbie Goodhue in December 2006 and a report by Dr. Trevor Orr in March 2007, it became apparent that the fill used beneath the floor slabs contained pyrite and that, as a consequence of oxidation of the pyrite, gypsum had formed. It was known that the chemical processes involved cause expansion.

This finding had significant implications as the client had used the same fill under about a thousand homes on three estates built at a similar time in the north Dublin area. The problem did not appear to have been experienced previously in Ireland and hence the critical issue was the necessity to confirm that this was the cause of the damage, and if so, to determine the most appropriate remediation.

From a literature review it became apparent that similar problems had occured in Canada and it was decided Golder should be asked to become involved. It was considered they would be able to deal with the geotechnical aspects as they had considerable world-wide experience and had worked on the pyrite problems in Canada.

Initial Inspection and Prognosis

Engineers and architects face significant problems in identifying pyrite-related damage in the early stages when it can be mistaken for normal shrinkage cracking etc. Most builders will treat the damage as normal snagging and will only become puzzled and suspicious when there is recurring damage. It was this recurrence of remediated damage which led to further investigation of the initial housing development and the same scenario has been encountered on many other sites.

One of the questions raised most frequently by both clients and homeowners at the early stages is whether the damage will stabilise, can be stabilised, or whether it will continue for some time in the future. As a number of factors are involved in the rate of heave as well as where and how it will be manifested, this is extremely difficult to answer satisfactorily and in all cases, significant investigation is required to clarify the extent of the problem.

Methods for Describing, Investigating and Monitoring Damage

Engineers are accustomed to describing wall and floor cracking and its remediation, using the guidance given in BRE Digest 251—*Assessment of damage in low-rise buildings* (1995, revised 2011). While this Digest is a very useful tool in categorising visual damage, I must stress that it is *not*, by its own admission, to be used in determining the appropriate remediation for *progressive* damage.

Under the section *Classification of Damage* it stresses that …*The classification relates only to visible damage at a given time and not its cause or possible progression which should be considered separately*… and also that… *Great care must be taken to ensure that the classification of damage is not based solely on crack width since this factor alone can produce a misleading concept of the true scale of the damage. It is ease of repair of the damage which is the key factor in determining the overall category of damage for the whole building.*

Engineers should proceed with caution during the initial inspection of a property suspected of suffering pyrite-related damage as they will be faced with many critical and potentially contentious considerations. Amongst these are:

(a) Where is the treatment of this problem going, and what significance will my report have?
(b) Am I looking at a property in isolation or is it possible to examine adjacent properties in the development to establish trends?
(c) How much is known of the source of the stone filling (quarry history)?
(d) Should I be advising testing of the stone at this stage, which can be a sizeable expense for a homeowner?

If the problem is likely to go to court or arbitration then a systematic Method Statement should be agreed in advance between the client's legal advisers and the engineer, who at this stage should have advised the client to engage the services of specialist geotechnical experts.

The inspection should record all damage meticulously on floor plans and wall elevations with the use of sketches and photos. Crack widths should be measured using appropriate methods.

It is also worthwhile to mark and date crack termination points (see Figs. 2 and 3). Any evidence of previous repairs should also be noted, particularly repairs that do not appear to have been successful i.e. where damage has re-appeared.

When preparing these records it should be appreciated that further inspections may be carried out in the future. Indeed, they can be very useful in establishing progression, which is a very significant feature of pyrite-related damage and can be

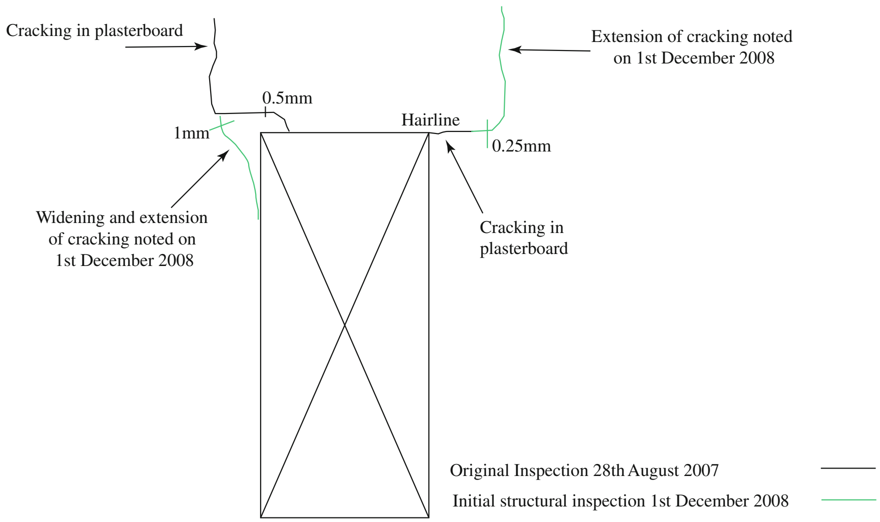


Fig. 2 Damage recorded in an internal wall of a house indicating progression over an interval of 15 months

very important in confirming that the damage is not related to other causes, e.g. consolidation of the fill, drying out of plaster etc.

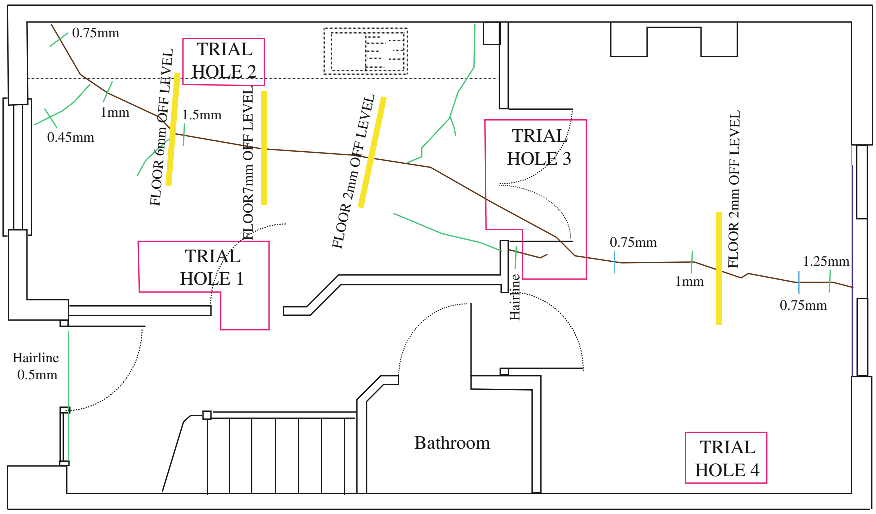
Mechanism of Heave/Response of Structures

Experience of inspection, testing and reporting before, during and after remediation on a wide range of projects since 2007 has indicated that the effects of pyritic stone infill differ, depending on a number of aspects of the structural design. It is clear that a complex interaction takes place between the expanding stone infill, the ground floor, the rising walls and foundations, and the superstructure (Fig. 4).

Where the stone infill is very confined, such as adjacent to party walls and internal rising walls, very large forces are developed which cause the walls to be lifted and the formation of horizontal cracks in the rising walls. Where the stone infill is less confined, such as at external walls where outward movement can occur, the forces generated by the expanding stone infill can be relieved or partially relieved.

Continuing lateral pressure causes outward stress on the external rising walls and this can lead to cracking and lateral displacements (Fig. 5). The movement is not always obvious, but during the remedial works evidence of the lateral pressures exerted by the fill was found in numerous properties.

In some properties, sudden apparent rises were noted in the ground floor slab within a number of days after the removal of the ground floor slab in the adjacent property i.e. on the other side of a common party wall.



Ground floor plan:

Items noted during structural inspection	19th February 2008	
Items noted during re-assessment on	24th April 2008	
Inspection on	4th + 5th March 2008	
Items noted during structural inspection	10th September 2008	
Positions of Trial Holes dug through floor	15th + 16th September 2008	

Fig. 3 Damage recorded in a floor slab during four visits over an 8 month period. Progression in the width and extent of cracking is highlighted. The locations of four exploratory trial pits are also shown

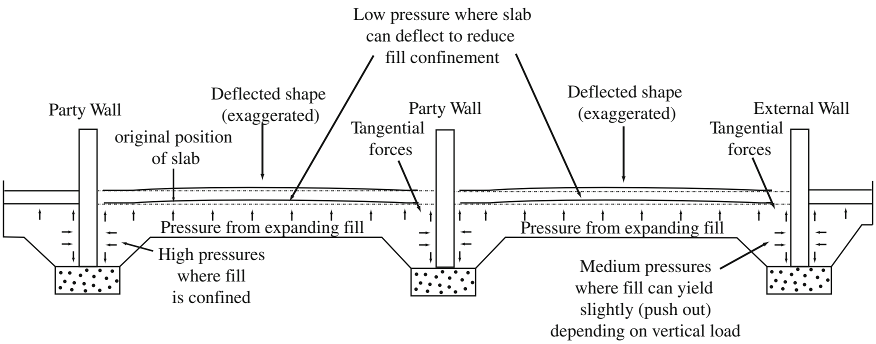


Fig. 4 Section through terrace showing notional sub-floor behaviour

Frictional forces between the expanding stone and rising wall elements can play a significant role in the way the structure responds to the swelling fill. Particularly where it is in a confined state, these can be very large (Fig. 6).

Fig. 5 Cracks created during lateral displacement of a rising wall

Before After

Fig. 6 Effect on the ground-bearing floor slab after the removal of fill in an adjacent property

A number of different values have been suggested in the literature for the expansive forces generated during pyritic heave. Maher et al. (2011) and Maher (2013) report pressures of up to some 600 kPa have been established for fill from remediated properties in Dublin while Bryant (2003) reported expansive forces of over 2,000 kPa. It should be noted that the expansion process can continue for many years; in the case of Llandough Hospital the remediation took place some 40 years after construction (Hawkins and Pinches 1987).

During the removal of the defective stone, horizontal cracking and gaps in the rising wall joints below ground floor level were often observed. These frequently extended through the full thickness of the rising walls and some cracks/gaps continued around the full periphery of the property. Where they passed through the internal rising walls, in some cases the aperture was in the order of 20 mm (Fig. 7).

Fig. 7 Horizontal gaps (up to 20 mm) observed in a rising wall immediately after the fill was removed in a localised trial pit (the balance of the fill beneath the floor slab was still in place at this time)

This in effect meant that frictional forces between the stone and the blockwork were sufficient to:

(a) break the mortar bond;
(b) lift the house by 20 mm, and
(c) hold the house up in its raised position.

These cracks/gaps were observed to close almost immediately after the slab and fill were fully removed and the forces that caused the building to rise were relieved, allowing the walls to return to their original positions.

Remedial works undertaken to date have confirmed that the interaction between the swelling stone, the sub-structure and the superstructure is complex and is likely to depend on many factors relating to the fill, its environment, the form of construction and time. Most structural engineers who have not experienced these processes would be very surprised at the pressures that can be developed in the fill if it is in a confined state. These pressures can be sufficient to fully lift a house and hold it in its raised position, as outlined above. The most basic calculation will show that this is possible with swelling pressures in the order of 100–200 kPa where the coefficient of friction between the stone and the blockwork is taken at, say, 0.45 (Fig. 8).

During the initial stages it became clear that remedial works carried out in one property could eventually be compromised to some extent by the continued swelling of an adjacent 'untreated' property. This can make the issue of Certification difficult and as a consequence it is recommended that remedial works are best carried out on a block by block basis.

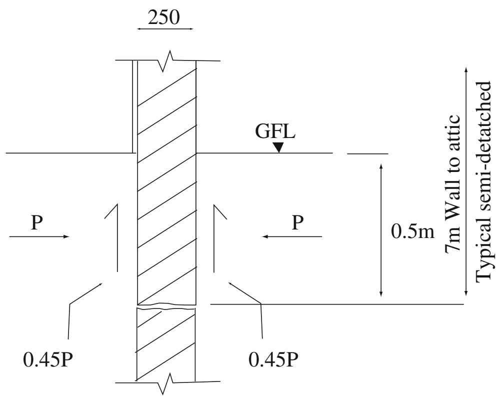


Fig. 8 Sample calculation of pressure required to lift a party wall

1. Ignoring Mortar

$2\,(0.45P) \times 0.5\text{m} = 7 \times 0.250 \times 22\ \text{kN} / \text{m}^3$
$2\,(0.45P) \times 0.5\text{m} = 39\ \text{kN} / \text{m}$

Add 6kN for incidental loading = 45 kN / m

$P = 45 / 0.45 = 100\ \text{kN} / \text{m}^2$

2. Assuming mortar must be broken first

Take mortar strength at $0.2\ \text{N} / \text{mm}^2$

Required additional force to break mortar and lift house =

$0.2 \times 215 \times 1000 / 1000 = 43\ \text{kN} / \text{m}$

Therefore pressure, P Value, in stone is

$(45 + 43) / 0.45 = 196\ \text{kN} / \text{m}^2$ say $200\ \text{kN} / \text{m}^2$

Experience has shown that structural damage in the Dublin area is normally manifest approximately 2–3 years after the floor slabs have been poured. However, both earlier and later instances have been recorded.

Examples of Damage Caused to Houses and Other Buildings

As noted above, the damage observed in any project affected by pyritic stone infill depends on many factors relating to the fill itself, its environment and also the type and form of construction. However, the following are typical of the damage observed in the Dublin area:

Fig. 9 Crack up to 7 mm wide across a floor which has risen 30 mm within a distance of 2.5 m

Ground Floor Slabs

Concrete ground-bearing floor slabs have risen and cracked. In standard houses, rises of around 25–30 mm across a normal width house are common, with crack apertures of up to 7 mm. A typical example of a crack extending through a sitting room is shown in Fig. 9.

Internal Walls (Cracking)

Cracking is common over door heads and where the internal wall, constructed on the floor slab, abuts the external wall founded on a strip footing (Fig. 10).

Fig. 10 Cracking through plaster and blockwork of internal wall

Fig. 11 Bowing of a stud wall pushed upwards by the rising floor slab

Bowing of Internal Stud Walls

Many of the internal walls in the affected buildings were constructed as plasterboard stud walls. Where the plasterboard rests directly on the floor slabs, the upward pressures cause distinct bowing (Fig. 11).

Skirtings/Architraves

A typical example of the twisting and bowing of timber skirtings is shown in Fig. 12. Door architraves are also frequently distorted by the pressure from the swelling stone.

Kitchen Units/Worktops

The rising/arching of the floor slab causes significant stress on fittings, particularly in kitchens where units may be damaged and worktops lifted/distorted. Figure 13 shows the effect on a worktop under stress from the rising floor but restrained by the wall tiles.

Fig. 12 Displacement of timber skirting

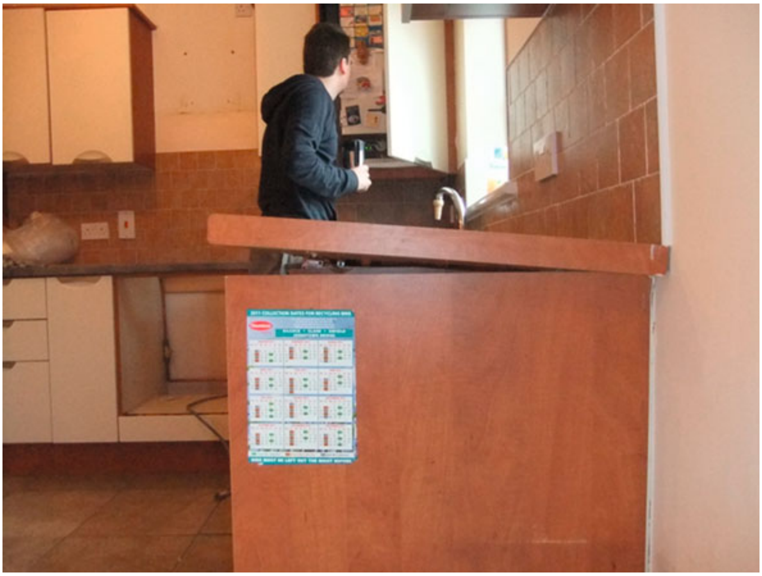


Fig. 13 Kitchen work top prised off its base

Doors Binding

There are many examples of doors binding against the rising ground floor slab (Fig. 14) or external paving (where the same pyritic stone has been used externally). In other situations, the door frame is forced upwards by the rising floor while the architrave in the centre does not rise, hence the door "catches" in the middle (Fig. 15).

Fig. 14 Bottom of door binding against floor

Fig. 15 Top of door binding against architrave

Lipping

Significant lipping can occur in the ground floor, generally at external doors/patio doors where the ground floor slab rises relative to the door threshold (Figs. 16 and 17).

External Plinth

In many types of construction, cracks occur where lateral pressures are applied to the rising walls. Typically these cracks develop where there is a structural

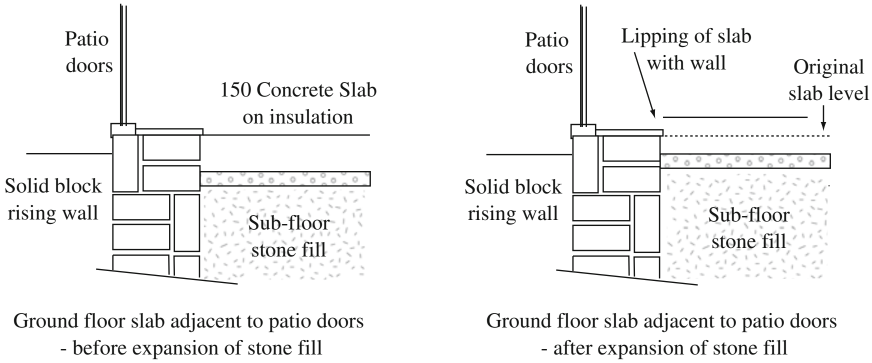


Fig. 16 Ground floor slab adjacent to patio doors, *before* and *after expansion* of the stone fill

Fig. 17 Typical lip at the location of a patio door (7 mm in this case)

weakness in the wall, such as where the damp proof course has been placed. In some instances this is accompanied by differential outward movement across the crack (Fig. 18).

External Leaf: Other Horizontal Gaps/Cracks

Significant horizontal gaps and cracks in the external leaf of cavity constructions have been noted. These develop where the inner leaf has been pushed up relative to the external leaf, notably in timber-framed houses. On one particular project this resulted in a gap of 40 mm at soffit level within 5 years (Figs. 19 and 20). In other situations a similar rise at the underside of cills has been observed.

Fig. 18 Cracking and displacement of external wall (plinth)

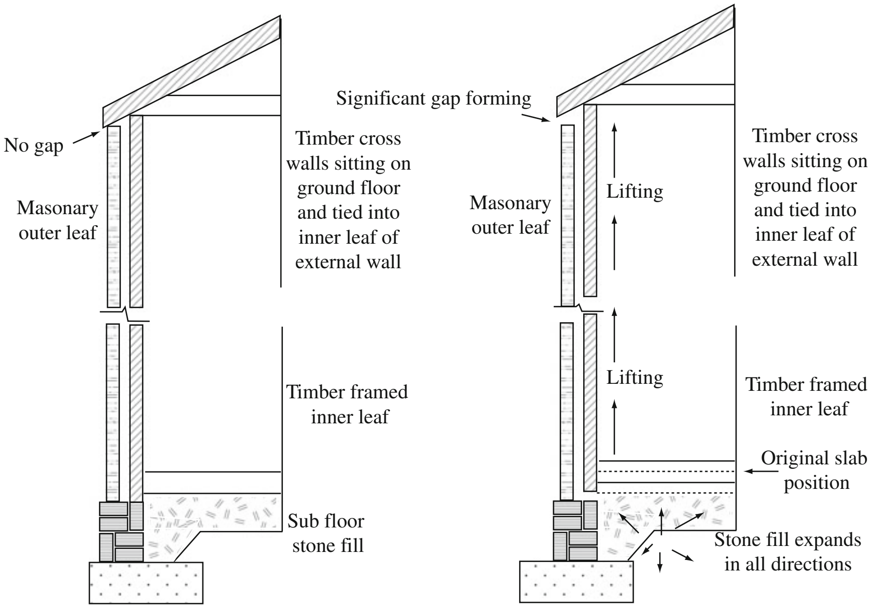


Fig. 19 Sketch indicating external wall *before* and *after* the internal leaf has been pushed upwards by the expanding fill

External Areas

Where pyritic fill has been used in external areas, various types of damage occur including cracking of concrete pavings, lipping at cold joints (between adjacent pours), gaps under kerbs and general lifting and differential movements in paved

Fig. 20 Gap of some 40 mm which developed at eaves level within 5 years of construction

areas. Possible damage to underground services from swelling stone is also a concern. Horizontal gaps have been observed in many manholes and service chambers (Figs. 21 and 22).

Concrete Attack

During the remediation works, evidence of gypsum growing on the rising walls was often observed. It was clear that if the fill were not removed, with time the concrete/concrete blocks could suffer sulphate attack.

Fig. 21 Pavement cracking near manhole

Fig. 22 12 mm gap near top of manhole

Parameters in Defining Appropriate Remediation

The key issues that need to be considered before appropriate remediation can be specified can be summarized as follows:

(a) What level of pyrite is in the stone and at what stage of oxidation is it? Based on these levels, is the oxidation (and consequential swelling) likely to continue in the future, and over what period?
(b) What is the quality of the stone and does it comply with current codes and guidelines (NRA SRW, SR 21, BRE Special Digest 1, TRL 447, Canadian Standard CTQ M200) with regards to aggregate grading and strength, sulphide, total sulphur and pyrite/equivalent pyrite.
(c) Is the observed damage consistent with swelling of the sub-floor fill?
(d) Is the level of sulphates in the stone sufficient to raise concerns about the possibility of chemical attack on concrete elements in close proximity to the stone e.g. block rising walls, foundations etc.?
(e) Is there any evidence of progression in the observed damage?
(f) Is there any evidence of damage to the external walls of the building?

There is to date very little definitive guidance available to engineers from Government or other regulatory sources. The guidance currently available in the form of SR21 is open to some question and is certainly not definitive. It is important that engineers, both structural and geotechnical, and other specialists practising in the field, should be brought together to aid Government in the formulation of definitive guidelines and recommendations.

Remediation and Certification

To date, remediation has entailed the complete removal of the defective stone and its replacement with stone of approved quality. The remediation work demands careful planning and an agreed practical method statement and quality control measures should be in place in advance of the works commencing on site. A variety of issues are likely to emerge during remediation which may include:

(a) Sequencing of the works to minimise possible further damage to retained elements of the structures while allowing the remediation to proceed as expeditiously as possible.
(b) Temporary stability, particularly of sub-structure works, at all stages.
(c) Replacement/retention of underground services.
(d) Addressing items of sub-standard construction exposed by the remedial works.
(e) Repairs to cracking etc. in elements to be retained.

Some of these issues can give rise to 'differences of opinion' between the Engineer and the Contractor and also possibly with the owners' technical advisers. Despite the fact that the Contractor may be his client, the Engineer must steer a fair and impartial course during the remediation and must be mindful that, firstly, it is the homeowner's interest that is paramount and secondly that it is the Engineer who ultimately must certify the works.

Certification

This will be based on confirmation that:

(a) The house has been so constructed that there is adequate bearing for the loads imposed, it is structurally sound and fit for habitation.
(b) The deleterious material has been removed and the new inert hardcore has been properly installed.
(c) Structural concrete has not been adversely affected and/or has been dealt with appropriately.
(d) Any significant building defects have been addressed.
(e) Services have been correctly reinstated.

Expert Witness and Expert Reports in Respect of Legal Actions/Arbitrations

Expert Witness

The brief of the Expert Witness will be provided by the legal team, but the following points are relevant in all cases:

1. The Expert Witness is required to provide information which is likely to be outside the experience and knowledge of others appearing at the Court/Arbitration.
2. The Expert's duty is, first and foremost, to the Court.
3. The Expert must be properly qualified to give an Opinion.
4. Even the most distinguished Experts may disagree and hence the Expert Witness must be able to rigorously defend their Opinion under formal examination by the Court, if required.
5. Prior to a court hearing, the Expert will be asked to provide a report which will give the facts as he/she understands them and the basis for their professional Opinion. This will involve the formation of a hypothesis, the testing of that hypothesis using a reliable methodology, the examination of the results and the drawing of a conclusion.

Summary and Conclusions

This chapter discusses some issues related to a Structural Engineer's involvement in cases of heave due to pyritic infill placed beneath ground-bearing floor slabs and/or pavements.

Examples are given of the effect of the expansion of the fill in different situations and the factors which influence this.

The ways of determining whether the distress is due to pyritic heave are considered as, particularly in the early stages, the problems may easily (and perhaps rightly) be attributed to other causes.

To date, remediation has been based on the removal of all the deleterious material. Attention is drawn to the importance of sequencing the work and to the influence of adjacent buildings while the remediation is being undertaken.

The role of the Structural Engineer in both the remediation and subsequent certification is explained.

Acknowledgments I would like to thank my colleagues Paddy Darling and Martin Bennett for their invaluable and essential technical assistance. Also, Leonie Lawler, Lisa Drohan and Anna Viti for all their work in preparing the presentation and paper. Lastly, but certainly not least, many thanks to my wife Ann for all her encouragement and support.

References

Bryant, L. D. (2003). *Geotechnical problems with pyritic rock and soil*. Virginia Polytechnical Institute, Blacksburg, VA.

Building Research Establishment. (2001). Concrete in aggressive ground. BRE Special Digest 1, BRE, Garston.

Comité Technique Québécois D'étude Des Problèmes De Gonflement Associés à La Pyrite. (2001). Appraisal procedure for existing residential buildings, Procedure CTQ-M200, Version 2.0.

Hawkins, A. B., & Pinches, G. M. (1987). Cause and significance of heave at Llandough Hospital, Cardiff—a case history of ground floor heave due to gypsum growth. *Quarterly Journal of Engineering Geology, 20*, 41–57.

Maher, M. L. J. (2013). *The Canadian pyrite experience and comparisons with the Irish problems*. Berlin: Springer, pp 36.

Maher, M. L. J., Azzie, B., Gray, C., & Hunt, J. (2011). *A large scale laboratory swell test to establish the susceptibility to expansion of crushed rock containing pyrite.* 14th Pan-Am Geotechnical Conference, Toronto, Canada.

National Roads Authority. (2000). "Specification for Road Works", Manual of contract documents for road works (Vol. 1).

Reid, J. M., Czerewko, M. A., & Cripps, J. C. (2001). Sulfate specification for structural backfills. TRL Report 447, TRL Ltd, Crowthorne.