Clay Shrinkage and the risk of subsidence

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Introduction

The Natural Perils Directory (NPD) system contains a number of models for assessing the environmental risks to building structures from subsidence, flood and storm (Hallett *et al.* 1994). The detailed soil data in the system enable sophisticated differentiation of the soil properties that can cause subsidence. These data uniquely identify the soil type in each hectare (ha) or 100m x 100m block of land in Great Britain. They provide national coverage, are unique and are, without doubt, the most detailed available for any kind of soil-related risk assessment in the environmental sector.

One of the most widespread problems for the insurance and re-insurance industry is the risk of damage to buildings resulting from soil movement or subsidence. Shrinkage of clays is the most common cause of soil related subsidence and it is therefore possible to use the NPD system to accurately predict areas by Royal Mail Postcode system down to Postcode Unit level where there is a significant risk of subsidence from this cause.

This paper describes the scientific principles underlying clay shrinkage and examines the relationship with ground movement. Shrinkage results from drying of the soil and the amount of drying can be predicted from climatic data. The exact relationship between amounts of ground movement and actual damage to buildings is very difficult to establish, but it is reasonable to assume that the more the ground moves as a result of clay shrinkage, the greater will be the potential damage to buildings located thereon. Such damage can be predicted on a national basis with a high degree of confidence. However, subsidence risk can be exacerbated by local factors such proximity of trees and drains. Ideally, to use the risk assessments for directly setting insurance rates, a model is needed that relates amounts of ground movement to building damage, and subsequently costs of repairs.

Risk assessment and managment

A *risk* is the chance of a bad consequence or loss. Another definition of *risk* is the chance that some undesirable event may occur. *Risk assessment* involves the identification of the *risk*, and the measurement of the exposure to that risk. The response to risk assessment may be to initiate categorisation of the risk and/or to introduce measures to manage the risk. In some cases, the risk may simply be accepted. Such r*isk management* is a significant activity in the insurance industry.

The NPD system stores the geographical location and properties of soils across Great Britain (GB). There are about 1000 different soil types, called soil series, in GB each with a shrink-swell potential. This potential is realised under certain soil and climatic conditions and the appropriate climatic data are stored in the system as well. Using these data, the system provides a comprehensive methodology for identifying, and quantifying, the risk of subsidence; but to manage the assessed risk effectively, a relationship between shrinkage and actual damage to buildings (in the form of insurance claims) would be required. Insurers could use this information to manage their portfolio, to assess the exposure to risk of subsidence, to balance the premium income with capital assets and to optimise re-insurance coverage.

Clay shrinkage

Among the inorganic particles that constitute the solid component of any soil, *clay* particles are the smallest, generally defined as being <0.002 mm in size (equivalent spherical diameter, esd). Clay particles occur in most kinds of soil but they only begin to exert a strong influence on the behaviour of the whole soil where there is in excess of 35 per cent (by weight) of clay-sized material present.

Because clay particles are very small and commonly in the form of plates, there is an immense surface area to which water can be attracted. Most common kinds of clay have two layers of atoms, but some have three, and are able to hold additional water between their layers, in addition to surface attraction or inter-crystalline absorption of water. Clays of this kind, commonly known as smectites, have the capacity to shrink and swell the most and this family of clays is widespread in British soils.

The moisture content of undisturbed clays does not change greatly and consequently there are few changes in volume. The situation is very different, however, when clays are exposed at or near the ground surface (upper 2m) or especially if vegetation is rooting in them. This is because the roots of plants extract moisture from the soil to support growth (transpiration). Together with *evaporation* from soil and plant surfaces, the total moisture removed by these proceses is termed *evapotranspiration.*

Where soil moisture is continuously being replenished by rainfall, the soil itself will be unaffected by this removal of moisture as there is no net loss. In many parts of Britain, particularly in the south and east, summer rainfall is small and is exceeded by evapotranspiration. During the summer months in these areas, it is common for water reserves not to be replenished by rainfall, so soil moisture deficits occur.

The water being removed from the soil by plants leads to a reduction in soil volume and the consequent shrinkage causes stress in susceptible soil materials (Jones *et al.* 1995). The foundations located int soil may then move and cause damage to building structures above. This problem can be exacerbated by the fact that the soil beneath the structure may not dry out uniformly, so that any lateral pressure exerted on the building foundation is made effectively greater. The presence of trees and drains can lead to increased damage.

Detailed measurements of the shrinkage of clay soils have been made by Cranfield's soil physical laboratory (Reeve and Hall 1978). The data assembled on a range of clays with differing mineralogy are unique in the UK and are only matched in Europe by smaller set of measurements in the Netherlands. This is because shrinkage measurements are time consuming and expensive. Some work on shrinkage has also been done in the US but the soil conditions there are quite different from Europe.

Shrinkage is the reduction in volume of a soil when moisture is expelled. It depends upon the amount of clay and the type of clay minerals present. Measurements have been made at specific soil suctions - negative pressures selected to simulate the mechanisms whereby water is extracted from soil particles (Hall *et al.* 1977).

Measurements of shrink-swell (SSWELL) give the volumetric shrinkage that occurs between suctions of 5 and 1500 kPa as a percentage of the volume at 5kPa. The measurements have been restricted mainly to mineral clayey soils, *i.e.* soils with <15 per cent organic matter and clay contents of >35 per cent (Reeve *et al.* 1980). From these data, an SSWELL potential has been assigned to each of the soil series in Great Britain.

An assessment of the soil SSWELL potential at 1m depth has been made for all soil series represented on the National Soil Map for England and Wales (Soil Survey Staff 1983). Five classes of SSWELL are recognized on the basis of predicted volumetric shrinkage between 5 and 1500 kPa, expressed as a percentage of the volume at 5 kPa. They are defined in Table 1.

For all soils with clayey textures at 1m depth, volumetric shrinkage has been predicted from the average bulk density (Db) at 1m depth (Hollis 1991), the relationship between bulk density and volumetric shrinkage being based on a limited data set that includes shrinkage parameters, plasticity, bulk density, particle-size distribution, organic carbon content and cation exchange capacity (CEC) for selected horizons.

Table 1. Shrink-swell classes

SSWELL class	SSWELL	Shrinkage (vol) %
Very Low	VL	<3.0
Low	L	3.0 - 5.0
Moderate	M	5.001 - 12.0
High	H	12.001 - 15.0
Very High	VH	>15.0

After Hollis (1991)

The regression analyses suggest that, at 1m depth, only Db is significantly correlated with volumetric shrinkage between 5 and 1500kPa. The equation (1) shows the relationship:

$$\text{Shrinkage (\%)} = 33.54 - 15.0\ \text{Db} \qquad 1$$

r=-0.7579, r2 = 0.5744

Average bulk densities of clayey horizons at 1m depth were determined from SSLRC's soil physical property database for the full range of substrate types upon which the classification of soils is based (Clayden and Hollis 1984). These bulk densities were then used to predict the average shrinkage (%) for each substrate typeand the results are shown in Table 2. Glacio-lacustrine clay, Clay-with-flints and Plateau drift, alluvium and Greyish Till and Head are the types of soil materials likely to shrink the most when water is expelled.

Table 2. Measured shrinkage for different substrate materials

Substrate type	Shrinkage (vol) %
Reddish Till and Head	8.6
Greyish Till and Head	10.7

Chalky Till and Head	9.4
Glacio-lacustrine clay	13.3
Clay with flints and Plateau drift	12.6
Alluvium	15.5
Soft shale	10.1
Reddish Marl (mudstone) [Spetchley series]	10.1 [13.5]
Clay and sand	11.8
Non-swelling clay	12.0
Swelling clay	12.8
Brownish swelling clay	14.0

After Hollis (1991)

Allocation of soil series to one of the SSWELL classes was then made using the criteria in Table 3.

Table 3. Shrink-swell classes related to soil parent materials (substrate types)

SSWELL class	Soil Criteria
Very Low	Lithoskeletal, gravelly, sandy, light loamy or light silty at 1m depth
Low	Medium loamy or medium silty at 1m depth UNLESS derived from Clay-with-flints/Plateau drift
Moderate	Medium loamy or medium silty at 1m depth AND derived from Clay-with-flints OR Clayey at 1m depth AND on Soft shales, Reddish Marl (except Spetchley series), Clay and Sand, Non-swelling Clay, or any Till or Head
High	Clayey at 1m depth AND on swelling clay, Clay-with-flints/Plateau drift or Glaciolacustrine clay OR Spetchley series
Very High	Clayey at 1m depth AND on Brownish swelling clay
High *	Alluvial clay or Peat at 1m depth - very high SSWELL potential that is not achieved unless effective drainage to at least 2m depth installed

After Hollis (1991)

Methodology - *Amount of shrinkage and subsidence risk*

A clay-related subsidence risk scheme was developed over the 4 years. The scheme has 9 classes from extremely high (1) to extremely low (9) (see Table 4). This scheme combines the primary parameters of shrink-swell (SSWELL) and the potential soil moisture deficit (PSMD).

The PSMD is the potential deficit that can develop in a soil amply supplied with water and under a short, actively growing green crop. In an average year the maximum PSMD (Jones and Thomasson 1985) in the driest parts of south east England is between 225 and 250mm (rainfall equivalent). In dry years, the calculated maximum PSMD can exceed 350mm in these areas. The PSMD allows calculation of the potential amount of shrinkage.

The profile available water is the amount of water held between 5 and 1500 kPa and is the water available for plant growth. Clay soils commonly have profile available water contents between 125 and 160mm in the top 1.25m. Hence a clay soil subjected to PSMD>200mm will have lost virtually all of its available water in the upper 1.25m and probably down to 1.5m. The loss of this water results in shrinkage of clay materials. A clay soil can certainly be assumed to have lost all its available water to a depth of 1.5m when a PSMD of 250mm has developed.

Maximum shrinkage for the SSWELL classes is given in Table 2. As a general rule, some very high SSWELL alluvial clays will not shrink as much as clays of similar potential because of the high ground water table.

Physically, shrinkage is a three-dimensional process - thus as well as reductions in the horizontal and lateral dimensions, shrinkage will occur in the vertical dimension *ie.* the ground surface is lowered. A schematic representation showing the relationships between actual shrinkage (vol %) and Max PSMD for SSWELL class, and clay-related subsidence risk class is given in Figure 1. The SSWELL class lines (PSMD vs shrinkage) are not based on actual measurments but curves can be fitted and these will have the form of soil moisture release curves. The clay-related subsidence risk class limits were fixed by expert judgement and effectively subdivide the SSWELL classes.

Table 4. Ground movement index

Ground Movement Index	Subsidence Risk Class	Subsidence Risk	Shrinkage vol% Centroid of class
1.00	Extremely Low	EL (9)	1.50
2.67	Very Low	VL (8)	4.00
3.83	Low	L (7)	5.75
4.83	Moderately low	ML (6)	7.25
6.00	Moderate	M (5)	9.00
7.33	Moderately high	MH (4)	11.00
8.67	High	H (3)	13.00
9.67	Very high	VH (2)	14.50
11.00	Extremely high	EH (1)	16.50
Equation 2	*Parameters*		
	Intercept	par. a	0.00
	Gradient	par. b	0.67

Ground movement index

An index of ground movement, that expresses the relative differences between the clay-related subsidence risk classes, has been compiled from the data (Table 4) and this is shown in Figure 2.

The results show that the amount of ground movement likely to cause subsidence in *extremely high (EH)* subsidence risk class is eleven times greater than that in the *extremely low (EL)* risk class. An equation (2) fitted to the data, with movement index on the *y-axis* and shrinkage on the *x-axis*, represents a straight line passing through the origin (intercept 0.0) with a slope of 0.67.

$$\text{Ground Movement Index} = 0.67(\text{Shrinkage}) \qquad (2)$$

The *movement index* is directly proportional to the shrinkage (vol%) and computed so that the *index* for the *EL* class is 1.0.

In the absence of data directly relating building damage to clay-related subsidence risk, the relationship in equation 2 should not be used for directly setting insurance rates. For example, there may be almost no risk of damage to buildings from clay-related subsidence when shrinkage is less than 3% by volume. Shrinkage between 7 and 9% (Moderate *[M]* class) might indicate a moderate risk of buildings damage but shrinkage of more than 15% by volume (Extremely High *[EH]* class) could lead to a much higher (by an order of magnitude) risk of damage.

Advice from structural engineers is needed to determine the type of relationship appropriate for financial modelling (it could be curvilinear) and **it is important to emphasise that the figures presented here are for shrinkage only and not actual damage to buildings.**

Conclusions

The clay-related subsidence risk classes are based on sound scientific principles and they are closely related to the actual shrinkage that takes place in clay soils under varying moisture conditions in Britain. These classes have been compared with the subsidence claims information of a large household insurer in the UK. The locations of subsidence claims correlated significantly (66%) with the higher clay-related subsidence risk classes as predicted by the NPD system.

However, the clay-related subsidence risk classes have not been validated directly against detailed information of damage to individual buildings and the subsequent costs of rehabilitation, as the data to do this are currently lacking. However, it is reasonable to assume that the greater the shrinkage of the soil at foundation depth the greater the likely damage from subsidence.

Acknowledgement

This report incorporates the results of research by a number of colleagues. The concepts were originally proposed by Michael Jarvis (SSLRC) and Professor Peter Bullock, Director of SSLRC, was part of the team that conducted the basic research on shrinkage of clayey soils in the 1970s. Stephen Hallett produced the first computerised version of the model and both he and James Gibbons have been responsible for the unique spatial applications software package NPD that is capable of assessing clay-related subsidence risk, as well as risks from other soil factors, flood and storm, down to Postcode Unit level. We also appreciate the contributions of both Stephen Hallett and Professor Bullock in the preparation of this manuscript.

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Figure 1

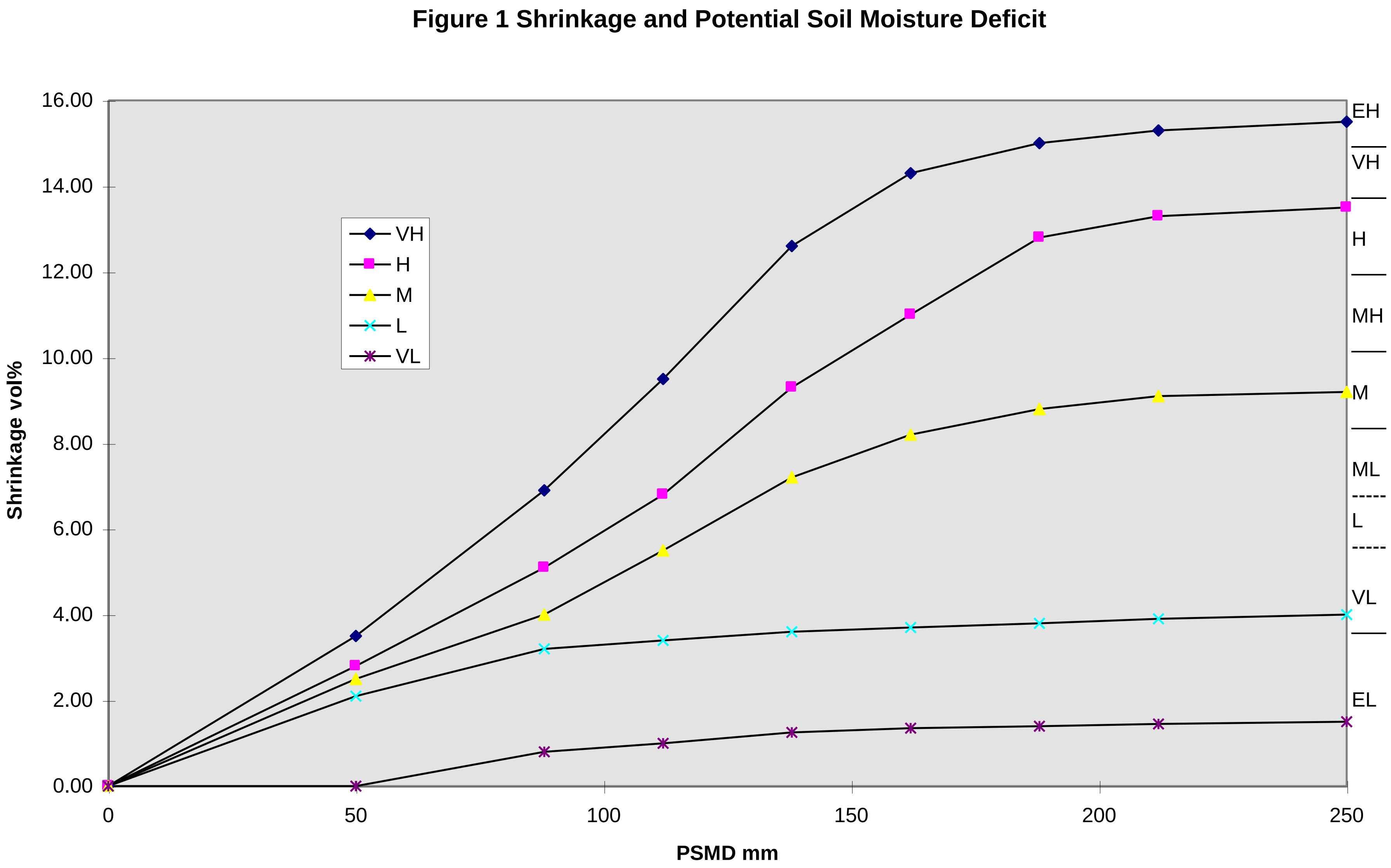
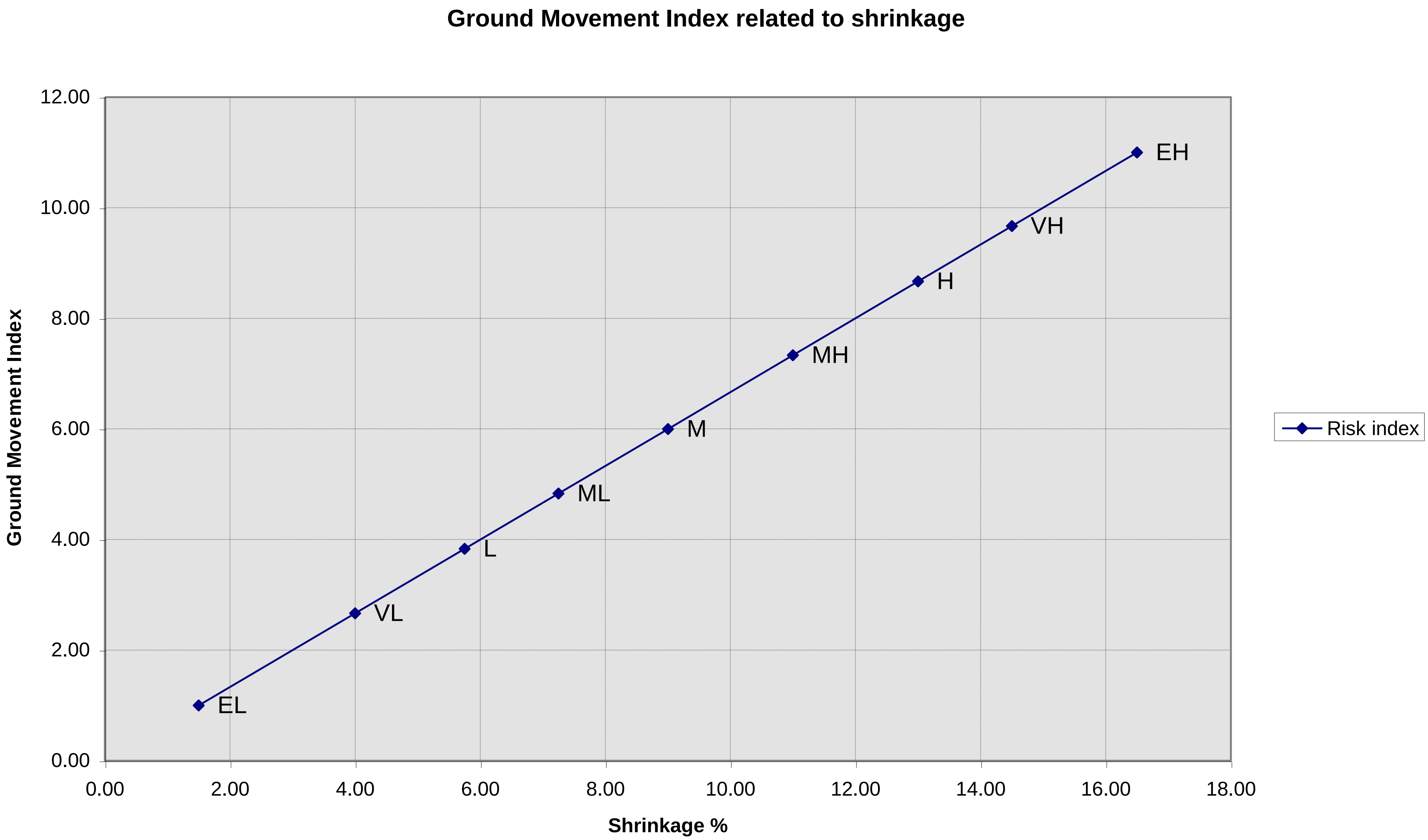


Figure 1 Shrinkage and Potential Soil Moisture Deficit
Shrinkage vol%
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
50
100
150
200
250
PSMD mm
VH
H
M
L
VL
EH
VH
H
MH
M
ML
L
VL
EL

Figure 2


Ground Movement Index related to shrinkage
Ground Movement Index
Shrinkage %
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
EL
VL
L
ML
M
MH
H
VH
EH
Risk index