Science and Technology, 4 (1999) 23-34

Computer-Aided Design for Estimating Foundation Uplift on Expansive Soils

Adnan A. Basma and Amer Ali Al-Rawas

Department of Civil Engineering, College of Engineering, Sultan Qaboos University, P.O.Box 33, Al-Khod 123, Muscat, Sultanate of Oman.

برنامج حاسوب لتقدير الأساس على تربة منتفخة

عدنان بسما وعامر الرواس

خلاصة : هذا البحث يعرض طريقة لحساب اندفاع الأساسات في موقع العمل تحت تأثير انتفاخ التربة . لقد تم إجراء فحص مخبري ل ٢٠٦ عينات من التربة أخذت من منطقة شبة صحراوية وذلك للحصول على نموذج رياضي للتنبؤ بقابلية الإنتفاخ . لقد بينت النتائج أن قابلية التربة للإنتفاخ تعتمد وبشكل كبير على نسبة الماء المبدئية ووحدة الوزن الجافة بالإضافة إلى نسبة الطين في التربة والضغط المبدئي . وباستخدام النموذج المطور تم كتابة برنامج حاسوب Advanced BASIC لحساب اندفاع الأساسات في الموقع . هذا البرنامج أضاف بعدا جديدا وبسيطا في نفس الوقت لتقدير اندفاع الأساسات . لقد تم إختبار هذا البرنامج باستخدام معطيات ميدانية وأعطى نتائج مشجعة .

ABSTRACT: This work presents a methodology to determine in-situ heave of foundations due to soil expansion. A total of 206 soil specimens from a semi-arid region (Irbid city in northern Jordan) were tested in the laboratory to produce a model for predicting the swell percent, SP. The results indicate that SP is strongly dependent on the placement conditions (initial water content and dry unit weight), clay content of the soil and the initial applied pressure. Utilizing this model, an Advanced BASIC computer program was written to evaluate in-situ heave. It was verified using actual field data. The program provides a simple means for approximately determining foundation heave.

In the field of geotechnical engineering it has long been recognized that swelling of expansive soils caused by moisture changes may result in considerable distresses or in severe damage to overlaying structures. In the past three decades or more, various investigators have conducted extensive studies to evaluate the important factors that influence swelling and to develop methods of analysis for predicting heave (Gromko, 1974; O'Neill and Ghazzaly, 1977; Mowafy and Baure, 1985; Basma, 1993). However, predicting soil behavior, in this case heave, in the laboratory is one thing and in the field is another. Evens under well-reproduced conditions in the lab, soils behave quite differently in-situ. One of the most influential soil properties that affects heave is moisture variation. The field moisture content of soils, in particular, its fluctuation from one season to another is very complex to estimate. Consequently, predicting the amount of foundation uplift due to in-situ heave is rather difficult. However, careful assessment of the appropriate soil properties along with the field conditions could lead to a good estimation of uplift.

The objective of this paper is to present a method by which uplift due to expansion of soils can be estimated in the field. To accomplish this task a mathematical model to predict the swelling potential was first sought. A total of 5 different soil specimens were selected from several sites in a semi-arid region and tested in the laboratory under various placement conditions and applied pressures. Utilizing the aforementioned model, an advanced BASIC computer program was written by which in-situ foundation heave could be assessed.

Soils of Selected Region

The soils were selected from Irbid City in Northern Jordan. The climate in the region is categorized as semi-arid. This is considered to be an excellent prerequisite for expansion, especially with the existing soils. The soils in this area are generally classified as highly plastic, extensively fissured, over-consolidated clay with an average clay content of 65%, liquid limit of 80%, plastic limit of 40% and shrinkage limit of 16% (Basma and Tuncer, 1991). The problem of expansion is the most predominant in the area. Many incidents were reported at different locations in and around the city in which residential buildings have suffered serious damage due to heave. Figure 1 shows the potential expansiveness of some selected soils based on the method proposed by Williams (1958) which is the one currently used world-wide. From this figure, it can be seen that clays in this area are classified as highly to very highly expansive.

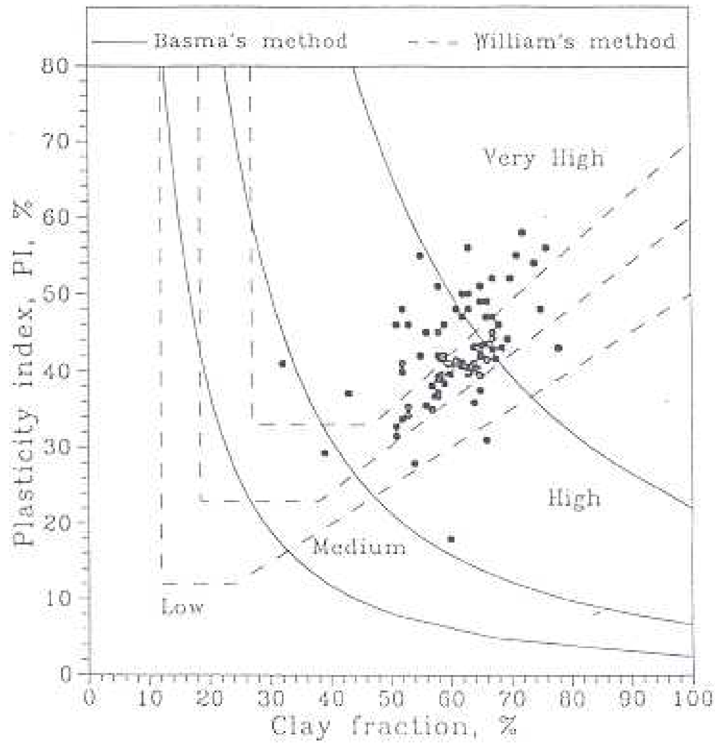


Figure 1. Potential expansiveness of some selected clays in the investigated region.

TABLE 1

Properties of Tested Soils.

	Soil Series				
Property	S1	S2	S3	S4	S5
Grain Size Characteristics					
Sand (4.75mm-75μm) %	27	10	5	4	2
Silt (75-2μm) %	39	42	36	26	100
Clay (<2μm) %	34	48	59	70	88
Consistency Limits					
Liquid Limit LL %	53.3	68.4	76.0	81.5	89.1
Plasticity Index PI %	26.4	35.3	42.0	44.1	42.2
Modified Proctor Compaction Characteristics					
γ_{dmax} kN/m^3	14.7	14.4	13.8	14.3	12.4
OWC %	21.8	25.9	26.8	29.5	33.6
Specific Gravity G_s	2.66	2.64	2.74	2.67	2.63
Unified Soil Classification	CL	CL	CH	ML-CL	ML

Soils and Testing Program

Laboratory tests were conducted on the selected soils to determine their basic and engineering characteristics. These are presented in Table 1. It is worth noting that the soils were extracted from sites in the vicinity of damaged structures. These damages were believed to have been heave related. Figure 2 illustrates the extent of damage to one of the buildings investigated. In this particular case, the crack was almost vertical with a width of about 1-cm at the bottom increasing to over 7-cm at the top. This type of damage is typically associated with soil expansion.

SAMPLE PREPARATION: To prepare the test specimens, an amount of soil was oven dried at 60°C for at least 72 hours. This temperature was used to minimize any major damage to the clay structure of the soils. The samples were thoroughly mixed with a calculated amount of water to give the required initial water content and further kneaded by hand to form a homogenous mixture. The wet soil was pressed into the consolidation ring (7.6 cm in diameter x 2.0 cm in height) and a pressure pad was applied at the sample surface. The specimen was then compacted to achieve a required dry unit weight using the modified Proctor compaction technique.

TEST PROGRAM: The test program consisted of single-oedometer swell tests on specimens prepared directly in the oedometer rings. This test consists of compacting a specimen into the oedometer ring then successively increasing the vertical load. The specimen is permitted to attain equilibrium deformation at each level of pressure. At a prescribed applied pressure, p, the sample is inundated and the expansion is measured with time. The maximum expansion induced by the addition of water, divided by the initial height of the specimen, expressed in percent, defines the swell percent, SP, at that particular pressure, p.

Discussion of Experimental Results

For the selected soils two test series were performed in which the water content and the dry unit weight were varied. These tests were conducted in such a way that three water contents (10, 20 and 30%) and three compaction dry unit weights (12, 14.5 and 16.5 kN/m^3) were used. It is important to point out that since the test program consisted of single-oedometer swell tests, several identical samples were compacted at the same initial water content and dry unit weight. These specimens correspond to a single placement condition tested under different applied pressures. The pressures used were 50, 100, 200, 400, 800 and 1600 kPa with at least 3 pressures applied on each sample depending on its degree of expansion. Consequently, a total of 206 specimens were tested in order to determine the effect of various parameters and properties SP. The outcome of the experimental work follows.

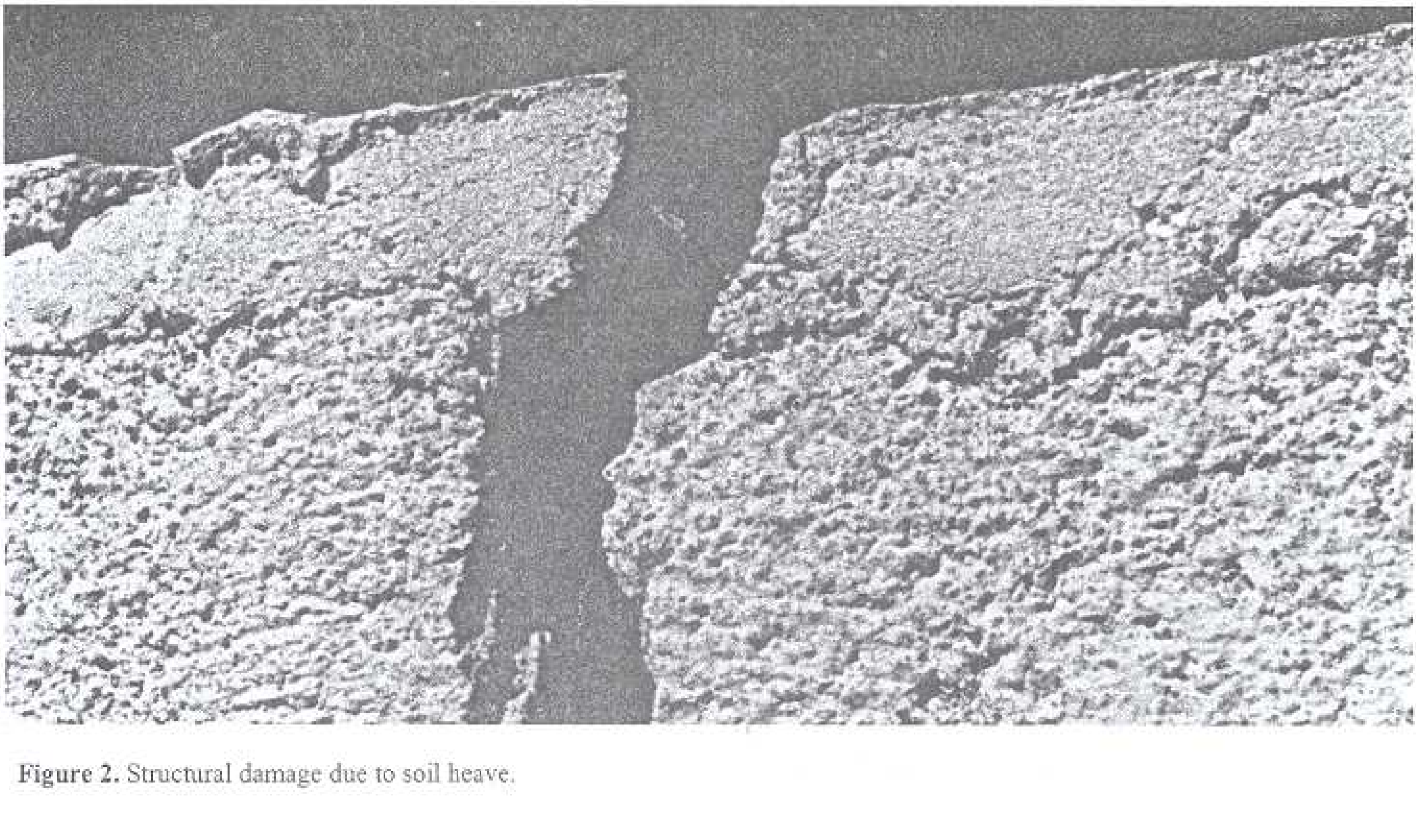


Figure 2. Structural damage due to soil heave.

INFLUENCE OF SOIL TYPE: The grain size distribution was used to identify the soil type by considering the effect of the clay fraction (< 2 μm), CF, on SP. The results are illustrated in Figure 3. The general trend in this figure suggests that higher CF implies higher SP at a particular applied wetting pressure, p. This observation corroborates earlier findings by Bandyopadhyay (1981) and Seed et al. (1962).

INFLUENCE OF COMPACTION PARAMETERS:

a) Initial Dry Unit Weight

The importance of the initial dry unit weight on SP is illustrated in Figure 4. This figure clearly indicates that for the soils used in this work, increasing the initial dry unit weight at a particular pressure and water content SP. The denser the soils are the lower the initial void ratios, thus, resulting in greater swell upon wetting.

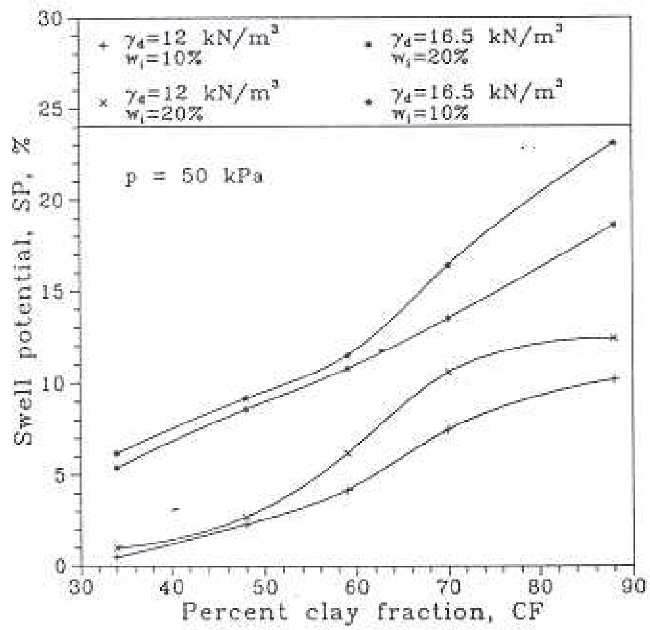


Figure 3. Influence of clay fraction on swelling potential.

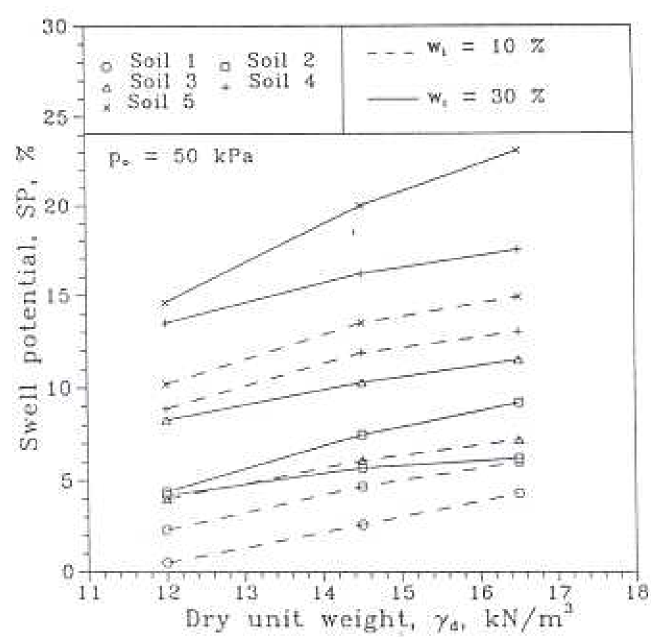


Figure 4. Influence of dry unit weight on swelling potential.

b) Initial Water Content

Figure 5 shows the significance of the compaction water content SP. This figure indicates that the wetter the soils were at compaction the lower was the SP at a particular dry unit weight and pressure at wetting. The swell percent was reduced because the initial bond provided by the fine fractions in the soil has already weakened due to the higher initial amount of water. In other words, higher initial water content reduces the metastable forces, and what remains from these forces to be reduced completely by wetting is less; as a result, less swell would occur.

c) Influence of Pressure at Wetting

The results of the swelling tests on the soils under different applied pressures prior to wetting are presented in Figure 6. It is noted in this figure the SP decreases with the pressure at wetting. This can be attributed to the fact that the initial applied pressure resists the swelling forces; as the pressure increases, the resistance increases, thus causing less swell.

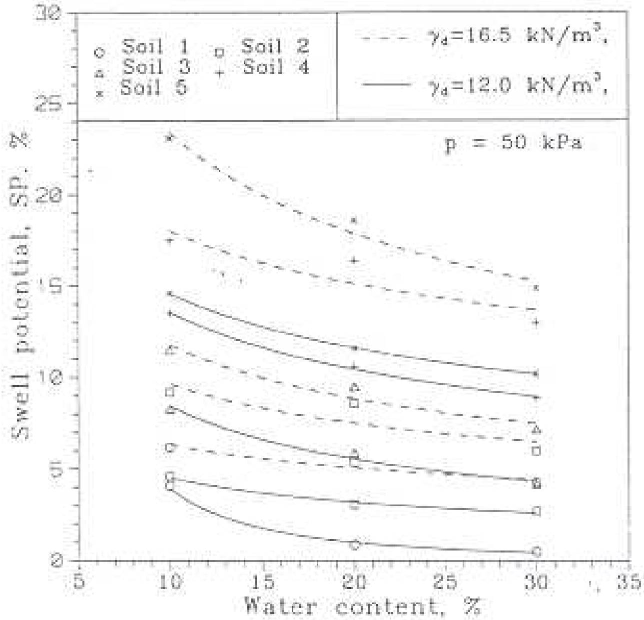


Figure 5. Influence of dry unit weight on swelling potential

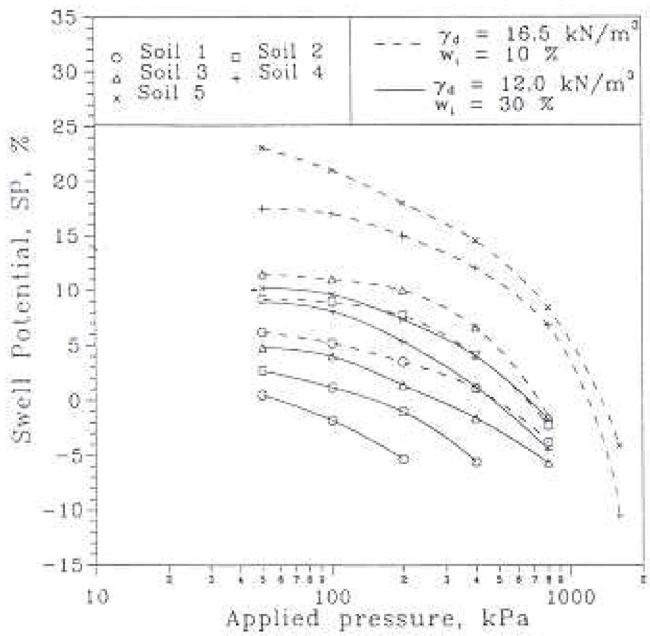


Figure 6. Influence of applied pressure on swelling potential.

Swelling Predictive Model

In the face of the complicated behavior of swelling soils and the various parameters that affect it, the ultimate aim would be the development of prediction tools that can, to some extent, reproduce real situations either in the laboratory or in the field. Generally, there are two alternative methods of investigation. The first is a full scale monitoring system that may extend for a long period of time coupled with some laboratory tests. The second is to produce prediction models (equations) that may accurately represent the swell behavior and relate it to several properties and conditions. This work and, in particular, this section is devoted to the second approach.

Utilizing the experimental data obtained by the swell tests, a multiple regression analysis was performed with the ultimate aim of producing a good predictive model for SP. The best-fit equation obtained was:

$$SP = 0.3CF - 0.16wi + 1.2\gamma_d - 0.025p^{1.15} - 18.8 \tag{1}$$

where SP is the swell percent, CF is the clay fraction in percent, wi is the initial water content in percent, γd is the compaction dry unit weight in kN/m3 and p is the pressure at wetting in kPa. The regression characteristics of this equation are shown in Table 2. From the data provided in this table, it is important to note the following:

a) The correlation coefficient r2 is 0.902 indicating a rather good regression fit. In geotechnical analysis, this value is considered to be relatively high especially when one considers the heterogeneous nature of soils.

b) The percent clay fraction in the soil seems to be the most significant variable affecting SP as indicated by the highest absolute t-value.

c) A zero value for the model significance F and the t-significance values for the coefficients indicate that both the model as well as the variables used are vital in assessing the swell potential at the indicated degrees of freedom.iv).

d) The 95% confidence interval (estimate range) is +4.743%. In statistical terms, this implies that the proposed model in Eq. 1 can predict the swell percent with reasonable accuracy (95%) within this specified range.

These observations clearly testify to the validity and goodness-of-fit of Eq. 1.

TABLE 2

Regression Output for Equation 1.

Correlation Coefficient, r^2	0.902			
Standard Err. Of Est, SEE	2.420			
95% Confidence Envelope	±4.743			
Number of Observations	206			
Degrees of Freedom	201			
Model F-Value	121.427			
Model Significance F	0			
Regression Constant	-18.80			
Independent Variables, X_i	CF	w_i	γ_d,	$p^{1.15}$
Units	%	%	kN/m^3	p in kPa
Coefficients of X_i	0.301	-0.160	1.211	-0.005
Std. Err. Of Coefficients	0.011	0.024	0.091	0.0002
Absolute t-Value	27.364	6.667	13.307	25.000
t-Significance	0.0	0.0	0.0	0.0

Calculation of Foundation Uplift

As was seen earlier, the clays selected for this work are highly expansive in nature. Foundations constructed on such difficult soils are usually subjected to high forces due to swelling. These forces induce heaving, cracking and breakup in the foundations, slabs, beams and columns of buildings. Other structures that suffer extensive damage due to soil heave are highway pavements.

The main cause of soil expansion is water, in particular, its variation from season to season. Such variations generally occur within a specific depth below the surface after which the soil moisture remains almost constant. This depth is defined as the "active zone". Consequently, the soil from the surface down to the active zone is expected to swell. However, the soil beneath the footing within the active zone will cause foundation heave. The depth of the active zone depends on many factors namely, rain intensity, rate of evaporation and soil permeability. To estimate the depth of the active zone, two sets of samples were extracted from four different locations in Irbid within the selected study area. The first set was obtained at the end of the rainy season (March) whereas the second set was obtained after the dry season (August). It was anticipated that these two sets would, respectively, provide the maximum and minimum soil moisture content. The samples were extracted from a depth within the first 10 meters below the surface. The water contents of the soils for both sets were estimated at every 0.25 m and are presented in Figure 7. As can be observed from this figure, the active zone for the selected locations ranges between 2.9m and 4.5m.

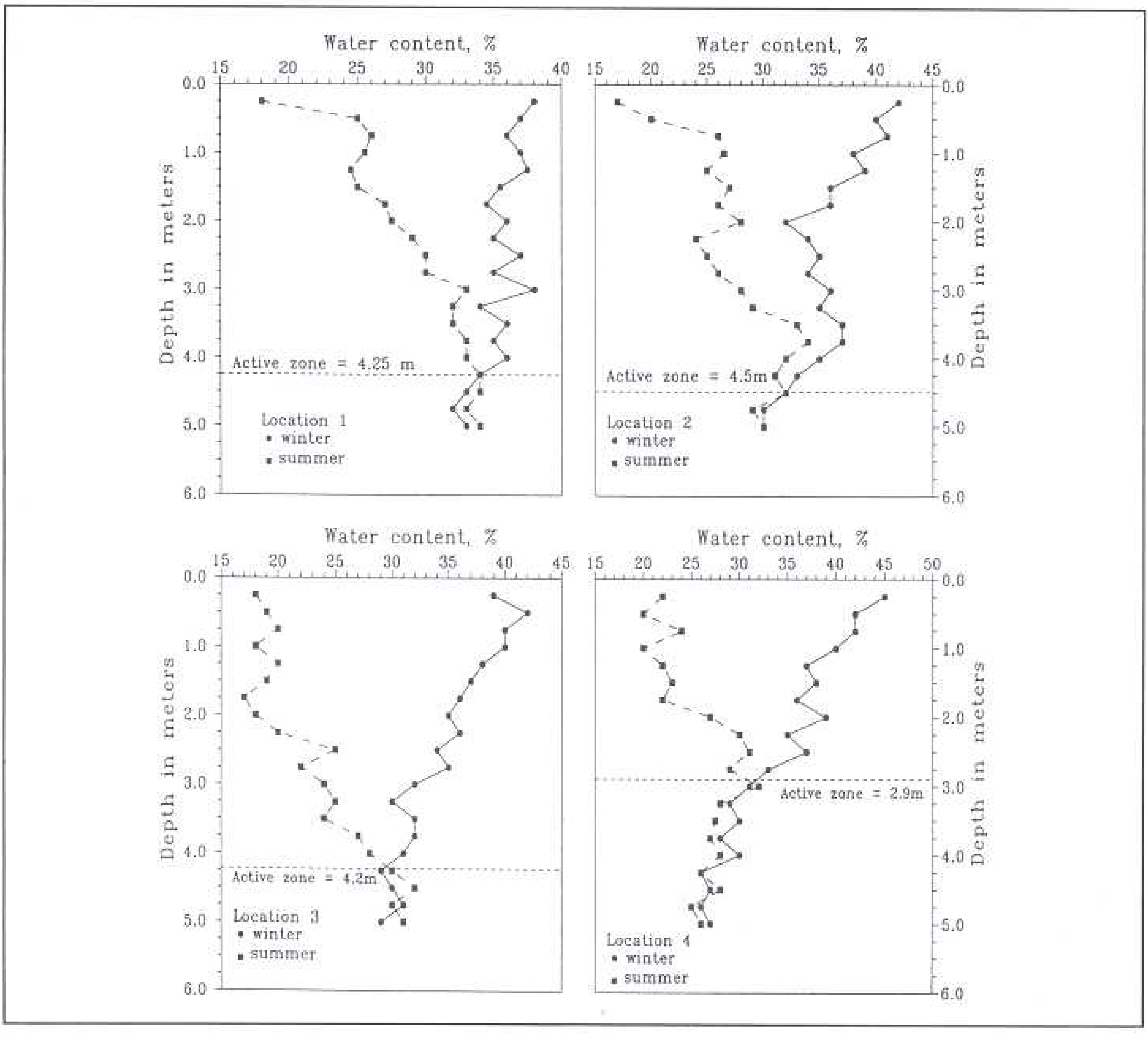


Figure 7. Variation of water content by seasons for four selected locations.

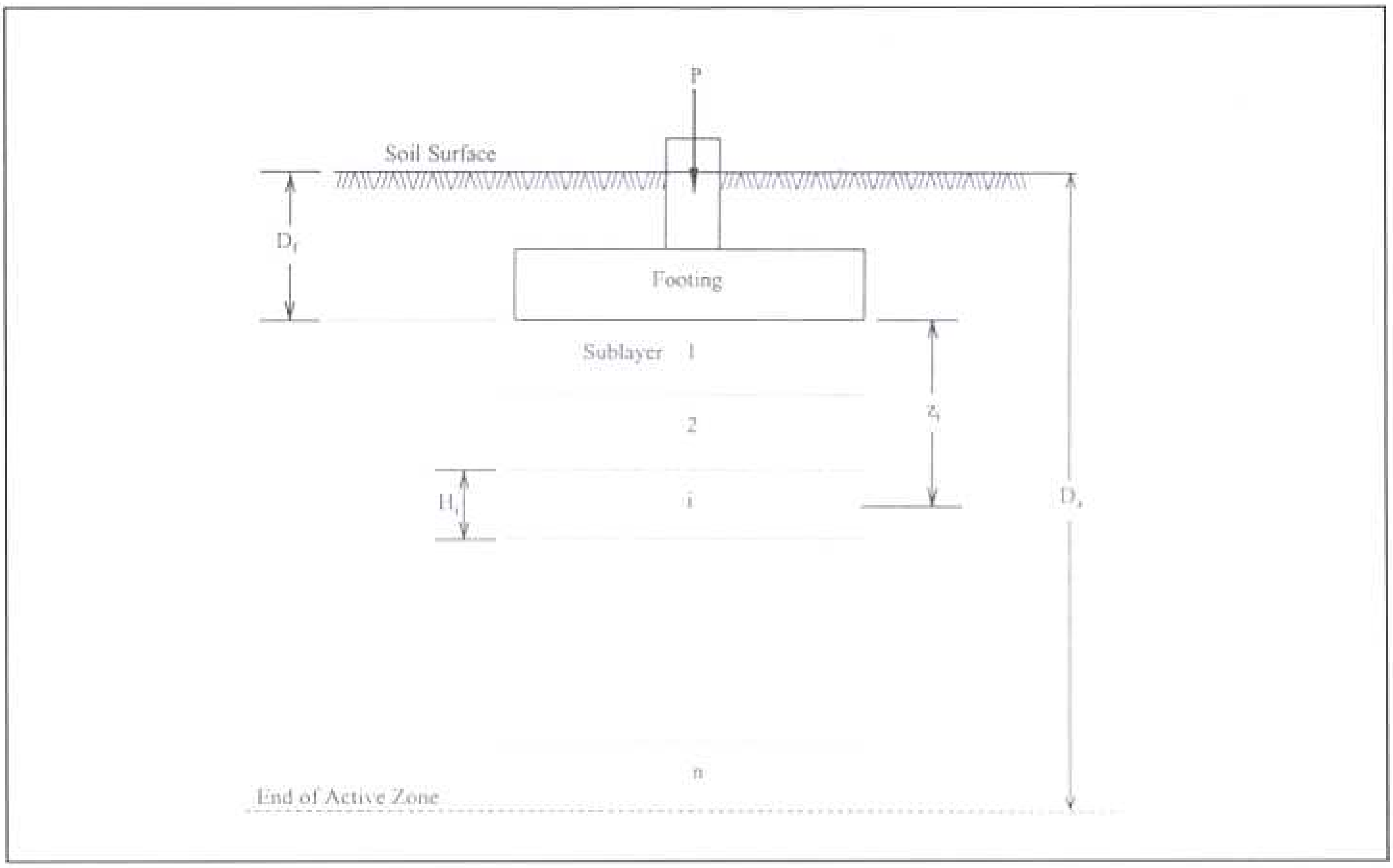


Figure 8. Definition of terms for heave calculation.

To determine the foundation uplift due to swelling the following steps are performed (refer to Figure 8):

1) Subdivide the soil layer under the footing down to the active zone into n sub-layers. The thickness of each layer will thus be

$$H_i = \frac{(D_a - D_f)}{n} \tag{2}$$

where D_a is the depth of the active zone and D_f is the depth of the footing below the surface. It should be noted that the larger the number of sub-layers is i.e. n, the more accurate the results are. Generally, an n value equals to 10 will suffice.

2) For each sub-layer calculate, at the center, the total vertical pressure, p, in the soil mass due to overburden, σ_o, and foundation load, q_z,

$$\sigma_o = \gamma_{ds}(z_i + D_f) \tag{3}$$

$$q_{zi} = \frac{P}{A_{zi}} \tag{4}$$

$$p_i = \sigma_o + q_{zi} \tag{5}$$

where z_i is the depth below the footing down to the center of layer i, P is the applied load, γ_{ds} is the summer dry unit weight and A_{zi} is the area using the common 2:1 method for stress calculations in soils.

3) Using the soil properties and the applied pressure p (Eq. 5) for each sub-layer "i", calculate the swell percent, SP_i, by Eq. 1.

4) Calculate the uplift, S_u, for each sub-layer and sum over all layers by the following equation.

$$S_u = \sum_{i=1}^{n} \frac{[SP_i\%](H_i)}{100\%} \tag{6}$$

In light of the numerous calculations involved (Eqs. 1, 2, 3, 4, 5, and 6), an advanced BASIC program was written to estimate foundation heave due to swelling. The listing of the program is shown in Figure 9. Figure 10 depicts a sample input/output and summary of calculation screens.

```
100 DIM Z(30), SIG(30), AZ(30), HV(30),
    UPL(30)
110 DIM PZ(30), P(30), SP(30), UP(30)
120 CLS:KEY OFF:COLOR  0,15
130 LOCATE 1,20:PRINT"┌";:FOR I = 1 TO 32
    :PRINT"─";:NEXT I:PRINT"┐"
140 LOCATE 2,20:PRINT"| Estimation of
    Foundation Heave |"
150 LOCATE 3,20:PRINT"|           Program
    for Heave Calculation Input/Output
    |"
160 LOCATE 4,20:PRINT"└";:FOR I = 1 TO 32:
    PRINT"─";:NEXT I:PRINT"┘"
170 LOCATE 6,5:COLOR 15,0:PRINT"Input the
    data
    below"
180 COLOR 2,0:LOCATE 8,5:PRINT"Depth of
    active
    zone, in meters = "
190 LOCATE 9,5:PRINT"    Depth of footing,
    in meters = "
200 COLOR 4,0:LOCATE 11,5:PRINT"
    Percent clay content = "
210 LOCATE 12,5:PRINT"        Average water
    content, % = "
220 LOCATE 13,5:PRINT" Average dry unit
    weignt, kN/m3 = "
230 COLOR 5,0:LOCATE 15,5:PRINT"
    Footing load, kN = "
240 LOCATE 16,5:PRINT"Footing dimensions in
    meters, L = "
250 LOCATE 17,5:PRINT"                  B =
    "
260 LOCATE 19,5:PRINT"          Allowable
    heave in cm =       (for undercut)"
270 COLOR 7,0:LOCATE 20,1:FOR I = 1 TO 80:
    PRINT"=";:NEXT I
280 COLOR 10,0:LOCATE 8,40:INPUT;"",DA
290 LOCATE 9,40:INPUT;"",DF
300 COLOR 12,0
310 COLOR 12,0:LOCATE 11,40:INPUT;"",C
320 LOCATE 12,40:INPUT;"",W
330 LOCATE 13,40:INPUT;"",GAM
340 COLOR 14,0:LOCATE 15,40:INPUT;"",PLOAD
350 LOCATE 16,40:INPUT;"",L
360 LOCATE 17,40:INPUT;"",B
370 LOCATE 19,40:INPUT;"",ALUP
380 NL = 10
390 D=DA-DF:DZ=D/NL:UP(0)=0:UPL(0)=0
400 SPP = (.28*C)+(1.1*GAM)-(.16*W)-19
410 FOR I = 1 TO NL
420 Z(I) = DZ*(I-.5)
430 SIG(I) = GAM*(1+(W/100))*(DF+Z(I))
440 AZ(I) = (L+Z(I))*(B+Z(I))
450 PZ(I) = PLOAD/AZ(I)
460 P(I) = SIG(I)+PZ(I)
470 REM
480 SP(I) = SPP-(.025*(P(I)^1.15))
490 UP(I) = SP(I)*DZ
500 UPL(I)=UPL(I-1) + UP(I)
510 NEXT I
520 FOR I = 1 TO NL
530 IF UPL(I) < ALUP THEN GOTO 560
540 JJ = I
550 GOTO 570
560 NEXT I
570 FR =1 - ((UPL(JJ)- ALUP) / (UPL(JJ) -
    UPL(JJ-1)))
580 UNCUT = DZ*((JJ-1)+FR)
590 HEAVE = UPL(10)
600 COLOR 15,0:LOCATE 21,5:PRINT
    "Output":COLOR 7,0
610 LOCATE 22,5:PRINT USING"Total uplift =
    ##.## cm";HEAVE
620 LOCATE 23,5:PRINT USING"Undercut =
    ##.## to";UNCUT;:PRINT USING" ##.## m
    below footing";D
630 LOCATE 25,17:PRINT"Do you want to see
    calculations ? (Y/N) ?
    ";:SEE$=INPUT$(1)
640 IF SEE$="Y" OR SEE$="y" THEN GOSUB 660
650 GOTO 960
660 CLS:COLOR 0,15
670 LOCATE 1,20:PRINT"┌";:FOR I = 1 TO 32:
    PRINT"─";:NEXT I:PRINT"┐"
680 LOCATE 2,20:PRINT"| Estimation of
    Foundation Heave |"
690 LOCATE 3,20:PRINT"|    Summary of
    Calculations      |"
700 LOCATE 4,20:PRINT"└";:FOR I = 1 TO 32:
    PRINT"─";:NEXT I:PRINT"┘"
710 COLOR 14,0:LOCATE 8,2:PRINT "  ─┬─┆─┬─  "
720  LOCATE 9,2:PRINT "┌──────┘ ┆ └──────┐"
730 LOCATE 10,2:PRINT "|         ┆        |"
740 LOCATE 11,2:PRINT "└─────────┆────────┘"
750 LOCATE 7,2:PRINT USING"P = ### kN"
    ;PLOAD
760 LOCATE 6,22:PRINT USING"  C = ##.# %;";
    C :LOCATE 6,35:PRINT USING"  w = ##.#
    %;"; W:LOCATE 6,50:PRINT USING "Gamad =
    ##.# kN/cu.m";GAM
770 LOCATE 7,22:PRINT USING" Df = ##.# m;";
    DF:LOCATE 7,35:PRINT USING" Da = ##.#
    m;"; DA:LOCATE 7,50:PRINT USING
    "Σhall.= ##.# cm";ALUP
780 LOCATE 8,22:PRINT USING"  L = ##.# m;";
    L:LOCATE 8,35:PRINT USING"  B = ##.#
    m";B
790 COLOR 10,0:   FOR I = 23 TO 73:LOCATE
    9,I:PRINT"=";:NEXT I
800 LOCATE 10,23:COLOR 10,0: PRINT"      d
    σo',    pz,      po,      SP,     Σh,
    "
810 LOCATE 11,23:COLOR 9,0:  PRINT" i     m
    kPa     kPa      kPa       %      cm  "
820 FOR I = 1 TO 10
830 LX= 11+(1*I)
840 LOCATE LX,2:PRINT "          ┆        "
850 COLOR 10,0:LOCATE LX,23:PRINT USING
    "##";I
860 CCL = 9:UPL(0) = 0
870 IF I = 10 THEN CCL = 10
880 ZZ = ZZ + DZ
890 COLOR CCL,0:LOCATE LX,26:PRINT USING"
    #.##";ZZ;:LOCATE LX,32:PRINT USING"
    ###.#"; SIG(I);:PRINT USING "
    ###.#";PZ(I);:PRINT USING"    ###.#";
    P(I);:PRINT USING "##.##";    SP(I);:
    PRINT USING "    ##.## ";UPL(I)
900 NEXT I
910 COLOR 10,0:   FOR I = 23 TO 73:LOCATE
    LX+1,I:PRINT"=";:NEXT I
920 COLOR 10,0:LOCATE LX+1,2:PRINT "
    ┆       "
930 LOCATE LX+2,2:PRINT "          CL      "
940 COLOR 14,0 :LOCATE LX+2,30:PRINT USING
    "Undercut = ##.## to";UNCUT;:PRINT
    USING" ##.## m below footing";D
950 COLOR 12,0:LOCATE 25,17:PRINT" Perform
    another run ? (Y/N) ? ";:RR$=INPUT$(1)
960 IF RR$ = "Y" OR RR$="y" THEN 120
970 LOCATE 25,17:PRINT"           Exit to
    DOS ? (Y/N) ?           ";:DR$=INPUT$(1)
980 IF DR$ = "n" OR RR$="N" THEN 630
990 REM  system
```

Figure 9. Listing of advanced BASIC program for heave calculation.

Estimation of Foundation Heave
Input/Output

Input the data below

Depth of active zone, in meters = **4.5**
Depth of footing, in meters = **2.0**

Percent clay content = **62.1**
Average water content, % = **26.1**
Average dry unit weight, kN/m3 = **14.2**

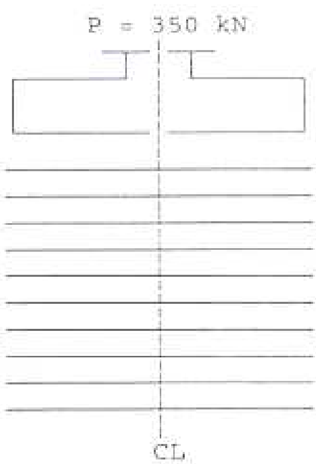
Footing load, kN = **350.0**
Footing dimensions in meters, L = **2.0**
B = **2.0**

Allowable heave in cm = **2.5** (for undercut)

Output
Total uplift = 7.10 cm
Undercut = 1.02 to 2.50 m below footing

Do you want to see calculations ? (Y/N) ?

Estimation of Foundation Heave
Summary of Calculations



C = 62.1 %; w = 26.1 %; Gamad = 14.2 kN/cu.m
Df = 2.0 m; Da = 4.5 m; Σhall = 2.5 cm
L = 2.0 m; B = 2.0 m

i	d m	σo′, kPa	pz, kPa	po, kPa	SP, %	Σh, cm
1	0.25	38.1	77.5	115.6	1.55	0.39
2	0.50	42.5	62.0	104.6	2.32	0.79
3	0.75	47.0	50.8	97.8	2.79	1.67
4	1.00	51.5	42.3	93.8	3.06	2.43
5	1.25	56.0	35.8	91.8	3.20	3.23
6	1.50	60.4	30.7	91.2	3.24	4.04
7	1.75	64.9	26.6	91.5	3.22	4.84
8	2.00	69.4	23.3	92.7	3.14	5.63
9	2.25	73.9	20.6	94.4	3.02	6.38
10	2.50	78.3	18.3	96.6	2.87	7.10

Undercut = 1.02 to 2.50 m below footing

Perform another run ? (Y/N) ?

Figure 10. Sample "Input/Output" and "summary of Calculations" screens.

It is interesting to observe that in addition to calculating the amount of heave, the program estimates the depth of the undercut. The undercut is defined as the depth that must be replaced by a non-expansive soil to reduce the heave to an allowable value (2.5 cm in this example). Furthermore, it is important to note that the program requires that the

TABLE 3

Constants a and b and Average Summer Water Contents for the Four Locations in Fig. 7

	Constants for Eq. 7					
Location	a	b	r^2	D_f, m	$(D_a - D_f)$, m	$\bar{w}_s$, %
1	25.2	0.19	0.90	2.0	2.25	31.2
2	23.6	0.18	0.86	2.0	2.50	29.1
3	19.7	0.20	0.76	2.0	2.20	24.6
4	23.6	0.12	0.71	2.0	0.90	26.3

average summer water content and the average unit weight be available to perform the calculations. The former can be approximated by integrating the variation of the summer water content with depth (Figure 7) between D_f and D_a and then dividing by (D_f - Da). Table 3 shows the constants a and b as well as the average summer water content by using the aforementioned approach for the four selected sites in Figure 7 with the general equation being

$$w(z) = a\ z^{\ b} \tag{7}$$

and

$$\bar{w}_s = \frac{a\left((D_a)^{b+1} - (D_f)^{b+1}\right)}{(b+1)(D_f - D_f)} \tag{8}$$

where w(z) and $\bar{w}_s$ and are respectively the change in water content with depth z and the average summer water content.

Verification of Computer Model by a Case Study

To verify the computer model presented in this paper, a case study for foundation uplift in Irbid City was used (Basma, 1991). The following summarizes the case study and field conditions:

In 1985, the city of Irbid decided to add an additional stand for spectators in the football stadium. A thorough investigation of the soil was performed and an allowable bearing capacity, qa of 83.3 kPa was used for design. This resulted in footings 2 m x 2 m in dimensions for calculated column loads of 325 kN. Construction started in October 1985. The top 2.25 meters of the soil was first excavated. As a construction precaution a 25cm thick flexible non-expansive selected fill material was used. The reinforced concrete footings were cast in place and the excavated soil was then compacted. The entire structure was completed in April of 1986. In August of the same year, cracks were observed in the outside walls in addition to several fissures in the columns and beams. Furthermore, a pond of accumulated water was observed under and around one of the footings in the vicinity of the cracked area. A team, including the first author, was called upon to address the problem. Investigation of this situation revealed that an old water pipeline running one meter below the footings (3 m below the surface) had cracked under the pressure induced by the footings causing a leak. This, consequently, resulted in a sudden increase in the moisture content of the soil. Under such an increase in moisture content, the soil heaved thereby causing uplift and differential uplift of footings. Careful field measurements indicated that the uplift was about 6.25cm. Specimens under the footing with maximum uplift were collected at various depths for laboratory testing. The experimental tests consisted of a) grain size distribution and mineralogical analysis, b) water content, unit weight and index properties determination, and c) swell measurements. The laboratory tests and field conditions yielded the following (details can be found in Basma, 1991):

Active zone = 4.0 m
Depth of footings = 2.5 m
Dimension of footing = 2 m x 2 m

Applied load, P = 325 kN
Average percent clay, C = 60.3%
Average summer water content, w = 24.3%
Average dry unit weight, γ_d = 14.4 kN/m^3

It should be noted that the above average values were estimated for the soil under the footing down to the active zone. With this data, the computer program estimated the foundation uplift to be 6.41cm (see Input/Output in Fig. 10) which compares well with the measured value of 6.25 cm.

Summary and Conclusions

The work herein presents an approach by which foundation uplift due to swelling can be estimated. A mathematical model was developed from conducting swell tests on five different soils. The specimens were prepared at various initial water contents, initial dry unit weights and tested under different pre-inundation pressures. Using the proposed model, an advanced BASIC computer program was written. The program predicts the expected heave for specific site conditions and estimated the depth of the undercut. From the results of this study the following conclusions are warranted,

a) The swell potential of an expansive soil is dependent on the clay content, initial placement condition and the pre-wetting pressure.
b) Swell potential increases with an increase in clay content and initial dry unit weight and a decrease in the initial water content and initial applied pressure.
c) The clay content of a soil was found to be the most significant variable affecting swelling of expansive clays.
d) The computer program provides a simple and easy means for estimating the uplift of a single footing under certain conditions. It was validated using a case study on foundation uplift.

References

BANDYOPADHYAY, S. S. 1981. Prediction of Swelling Potential for Natural Soils. *J. of Geotechnical Engineering Division, ASCE*. **107**(5), pp. 658-661.

BASMA, A. A. 1991. Estimating Uplift of Foundations Due to Expansion: A Case Study. *SEAGS J of Geotechnical Engineering*. **22**(2), pp. 217-232.

BASMA, A. A. 1993. Prediction of Expansion Degree for Natural Compacted Clays. *Geotechnical Testing J., ASTM*. **16**(4), pp. 542-550.

BASMA, A. A. and TUNCER, E.R. 1991. Effect of Lime on the Volume Change and Compressibility of Expansive Clays. *Transportation Research Board, TRR* **1295**, pp 54-61.

GROMKO, G. L.1974. Review of Expansive Soils. *J. of Geotechnical Engineering Division*, ASCE, **100**(6), pp. 667-687.

MOWAFY, Y. M. and BAURE, G. E. 1985. Prediction of Swell Pressure and Factors Affecting the Swell Behavior of Expansive Soils. *Transportation Research Board, TRR* **1032**, pp. 23-28.

O'NEILL, M. W. and GHAZZALY, O. I. 1977. Swell Potential Related to Building Performance. J. *of Geotechnical Engineering Division*, ASCE, **103**(13), pp. 1363-1379.

SEED, H. B., WOODWARD, R. J. and LUNDGREN, R. 1962. Prediction of Swelling Potential for Compacted Clays. *J. of Soil Mechanics and Foundation Engineering, ASCE*. **88**(3), pp. 53-87.

WILLIAMS A. A. B. discussion of paper. 1958. The Prediction of Total Heave from Double Oedometer Test. Trans., Symposium on Expansive Clays, South Africa Institute of Civil Engineers, pp. 24-26.

Received 22 September 1997
Accepted 18 September 1998