The ColMix Process of reinforcing soils
design and testing

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INTRODUCTION

ColMix is a technique used to improve soil by constructing columns of soil mixed with a binder. The process can be used to treat unstable embankments, improve the bearing capacity of the ground and repair polluted ground. This paper sets out a model which predicts the behaviour of ground reinforced by ColMix, thus allowing their design. The results of a test program carried out on ground improved by ColMix are presented and compared with the results of calculations based on the theoretical model.

BEHAVIOURAL MODEL

The elastic model presented here is able to predict the settlements of ground improved by reinforcing elements, e.g. ColMix, which cannot be considered as rigid relative to the surrounding soil. For these elements one expects a significant proportion of the load to be carried by skin friction.

Isolated Inclusion

Equilibrium of an isolated element requires that the variation of compressive stress in the inclusion with depth is in equilibrium with the skin friction,
$$\frac{\delta q_R}{\delta z} + \frac{p_R}{S_R}\tau_S = 0$$

The skin friction is equal to the product of the modulus of shearing of the soil and the sliding relative to the soil,
$$\tau_S = -G_S \frac{\delta w_R}{\delta r}$$

A classic observation of the settlements of soil around a deep foundation element shows that they can be approximated by an inversely proportional relationship with distance from the element centre,
$$w = w_R R / r$$

and as $w = w_R$ at $r = R$,
$$\frac{\delta w_R}{\delta r} = -\frac{w_R}{R}$$

So that in total
$$\frac{\delta^2 q_R}{\delta z^2} + \frac{p_R G_S}{R S_R}\frac{\delta w_R}{\delta z} = 0$$

Taking into account the elasticity of the reinforcement, the variation of the stress is defined by the differential equation,
$$\frac{\delta^2 q_R}{\delta z^2} - \frac{p_R G_S}{R.E_R S_R} q_R = 0$$

An additional constant, the characteristic length of load transfer from the reinforcement to the soil, l_{RS}, may be introduced, equal to the product of two values, $l_{RS} = d_R . m_{RS}$.

The first value is a length which depends only on the geometry of the inclusion, $d_R = \sqrt{\frac{RS_R}{p_R}}$

For circular or square inclusions (taking ϕ as equal to a side length), $d_R = \phi.\sqrt{1/8}$.

The second one is a dimensionless value which is equal to the ratio of the rigidity of the inclusion in connection with that of the soil, $m_{RS} = \sqrt{E_R / G_S}$.

For a reinforcement of infinite length, the variation of stress with depth is expressed by

$$q_R = q_{R0} . e^{-z/l_{RS}}$$

the settlement by,

$$w_R = \frac{q_{R0} . l_{RS}}{E_R} e^{-z/l_{RS}}$$

and

$$w_{R0} = q_{R0} . l_{RS} / E_R$$

and the mobilised skin friction at depth z by,

$$\tau_S = q_R . d_R / R . m_{RS} .$$

In reality the reinforcement has a finite length and the soil will not be homogeneous. Within each layer, the stress and the settlement at a depth z will be functions of two constants,

$$q = A . e^{-z/l_{RS}} + B . e^{z/l_{RS}}$$

and

$$w = \frac{A . l_{RS}}{E_R} . e^{-z/l_{RS}} - \frac{B . l_{RS}}{E_R} . e^{z/l_{RS}}$$

the characteristic length of transfer being defined from the characteristics of the inclusion - d_R, E_R, and of the soil, G_S, in the layer considered.

Knowing the stress, q_B, and the settlement, w_B, at the base of the layer, it is possible to calculate the constants A and B in the layer,

$$A = 0.5 . e^{h/l_{RS}} . (q_B + E_R . w_B / l_{RS})$$

and

$$B = 0.5 . e^{-h/l_{RS}} . (q_B - E_R . w_B / l_{RS}) .$$

The stress, q_T, the settlement, w_T, and the mobilised friction, τ_{ST}, at the top of the layer are deduced from,

$$q_T = A + B$$

$$w_T = (A - B) . l_{RS} / E_{RS}$$

and

$$\tau_{ST} = (A - B) . l_{RS} . G_S / E_{RS} . R$$

The stress, q_F, and the settlement, w_F, at the toe of the inclusion, are given by the relationship

$$w_F = q_F . l_F / E_F$$

in which the transfer length and the Young's modulus correspond to the characteristics of the foundation soil that is present at the toe of the inclusion.

Inclusions within a mass

The global behaviour of a reinforced mass is characterised by a uniform stress q_H and a uniform displacement w_H. However the actual stresses differ from these uniform values, the differences being q'_R and q'_S respectively. For the inclusion,

$$q'_R = q_R - q_H . E_R / E_H$$

where the homogeneous modulus

$$E_H = E_S (1 - t) + t . E_R .$$

Global equilibrium requires that,

$$q'_R . t + q'_S . (1 - t) = 0$$

and equilibrium of the inclusion section,

$$\frac{\delta q'_R}{\delta z} + \frac{p_R}{S_R} \tau_S = 0$$

The settlements also differ from the uniform settlement, and one can define a relative settlement of the inclusion in relation to that of the soil, $w' = w_R - w_S$.

One assumes here that the relative settlement is of the form $w' = -w'_R . R / r + f(r)$ and as the relative settlement is a minimum at the edge of the grid, $\delta w'_R / \delta r = -w'_R . (1 - t) / R$.

The differential equation that defines the difference between the uniform stress and the stress in the inclusion is therefore written, $$\frac{\delta^2 q'_R}{\delta z^2} + \frac{p_R . G_S .(1-t)}{R.S_R} . \frac{\delta w'}{\delta z} = 0$$

But as $w' = w'_R - w'_S$, $$\frac{\delta w'}{\delta z} = -\frac{q'_R}{E_R} + \frac{q'_S}{E_S}$$

and taking into account the relationship between q'_R and q'_S $$\frac{\delta w'}{\delta z} = -q'_R . \frac{E_H}{E_R . E_S .(1-t)}$$

One can therefore define a relative modulus of the inclusion in relation to the mass, $$E_{RM} = E_R . E_S .(1-t) / E_H .$$

Finally the variations of the differential stresses in the inclusion are modelled by,

$$\frac{\delta^2 q'_R}{\delta z^2} - \frac{p_R . G_S .(1-t)}{R.S_R . E_{RM}} . q'_R = 0$$

identical to the form of the differential equation that models the behaviour of an isolated inclusion.

It is therefore possible to define, in each layer, a length of depreciation of the difference of the stresses, l_D, different from the length l_{RS}, $l_D = d_R . m_{RM}$, in which the characteristic dimension is that of the inclusion, but where the ratio of the moduli is $m_{RM} = \sqrt{E_{RM} / G_S .(1-t)}$.

The variations of the stresses and differential settlements are therefore given by $$q'_R = C. e^{-z/l_D} + D. e^{z/l_D}$$

and $$w' = \frac{l_D}{E_{RM}}(C. e^{-z/l_D} - D. e^{z/l_D})$$

For each layer, it is therefore possible to calculate the constants C and D, knowing the values of q'_B and w'_B at the base, $$C = 0.5. e^{h/l_D} .(q'_B + E_{RM} . w'_B / l_D)$$

and $$D = 0.5. e^{-h/l_D} .(q'_B - E_{RM} . w'_B / l_D)$$

and, consequently, the differences q'_T and w'_T at the top of the layer, $$q'_T = C + D$$

and $$w'_T = l_D .(C - D) / E_{RM}$$

Knowing, that at the bottom of the inclusion, $w'_F = q'_F \, l_F / E_F .(1-t)$ in which the values l_F and E_F are as defined for an isolated inclusion.

For all analyses, it is necessary to adjust the conditions at the head of the inclusion, $w'_0 = 0$ in the case of a rigid slab and $q'_0 = q'_{RH0} - q_0$ in the case of a uniform load, a condition that reduces to $q'_0 = 0$ in the case of a distribution embankment.

TEST RESULTS FROM THE A14 EMBANKMENT

These works were located between the limestone cliff of St-Germain and the River Seine. The A14 highway comes out of tunnel from the cliff at 7.50m above the general ground level. A significant embankment, the height of which can reach 4.0m between the natural ground and the carriageway and 9.0m between the latter and the landscaped development, has been placed on soil reinforced by ColMix.

The Test Program

The test involved the construction of 8 ColMix columns with an injection of 6.07m^3 of grout per column (0.373m^3/ml). The grout consisted of 800kg of cement CLK45 and 20kg of bentonite C2 for each cubic metre. The column arrangement is shown in figure 1, and details of the soil layers and the instrumentation installed in tables 1 and 2 respectively.

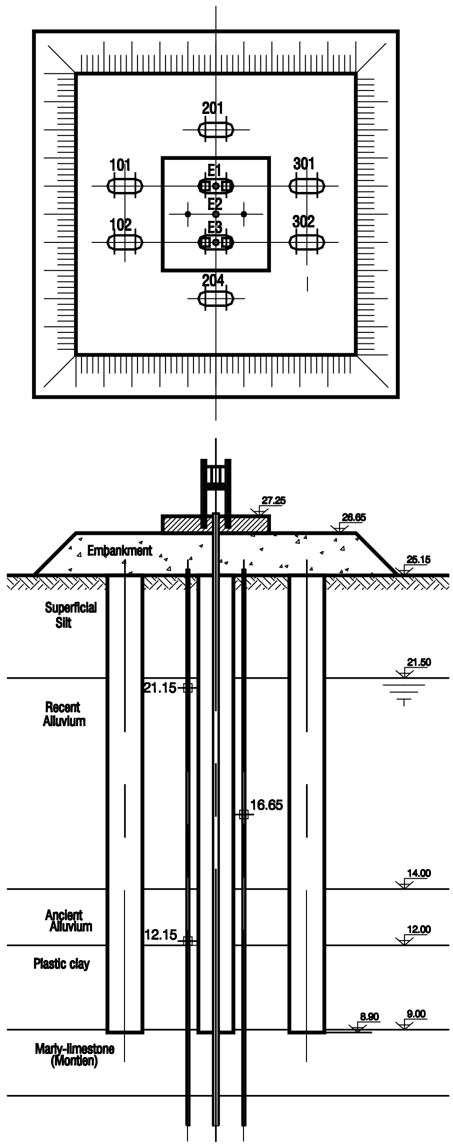


Figure 1 : Arrangement of test columns

Layer	Level NGF	E_P (MPa)
Slab	27.25	
Embankment	26.65	
Superficial silt	25.15	3.65
Recent alluvium	21.50	1.29
Ancient alluvium	14.00	3.83
Plastic clay	12.00	12.13
Marly-limestone (Montien)	9.00	53.72

Table 1 : Ground characteristics

Instrument	Level NGF	Position	Mark
Survey points	27.25	slab	R1 to R4
Total pressure	25.15	202 and 203	G1 to G4
Extensometer	4.25	202	E1
Extensometer	4.70	203	E3
Extensometer	3.35	centre	E2
Pore pressure	21.15 12.15	centre of the area	F1
"	16.65	"	F2

Table 2 : Instrumentation details

The various tests carried out included global loading of the 8 columns, direct loading onto a single column and also compression tests on core samples.

Crushing tests

The mortar of soil has been retrieved by coring in columns 301 and 302; and 19 samples were tested in the laboratory. The results are given in table 3 according to the original soil layer type. As was expected, the characteristics of the mortar of soil present a significant dispersion and are functions of the original layer. The sand mortar gives higher characteristics than that of silt mortar which are similarly higher to that of the clay mortar.

Soil layer	R_C (MPa) min./max./ave.	E_C (MPa)	E_C/R_C
Recent alluvium	1.44/4.50/2.99	2 538	849
Ancient alluvium	3.21/6.55/5.09	5 348	1050
Plastic clay	1.62/3.21/2.07	1 763	850

Table 3 : Results of crushing tests

Global loading

The first loading of the reinforced mass consisted of constructing a 1.5m thick embankment on an area 10.0m by 10.0m. Subsequently, a concrete slab, 0.6m thick and 3.8m by 4.0m was constructed above the central columns, 202 and 203. The slab was loaded by two beams of 120 tonnes each.

The loading program and the measured results are shown in figures 2 to 4. In each figure the behaviour of the columns is compared to the results given by the behavioural model (thick continuous line).

The settlements measured by the extensometers E1, in column 202, and E2, at the centre of the block within the soil, under the maximum test load of 240t are given in the figure 3. The modelling shows that the relatively significant difference between the topographical measurements and the extensometer measurements comes from the settlement of the embankment.

The total load measured on the central columns (202 and 203) by the total pressure cells is only a fraction, around 8%, of the load imposed on the slab. The model confirms the fact that most of the load is distributed by the embankment. This result is presented in figure 4.

Figure 2 : Slab settlement

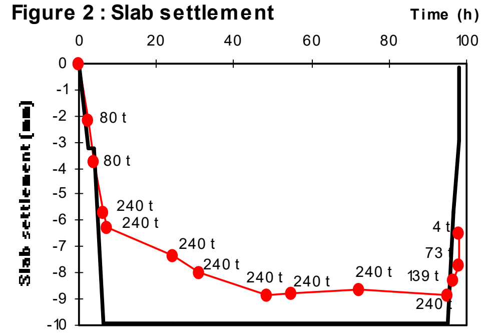


Figure 3 : Mass settlements

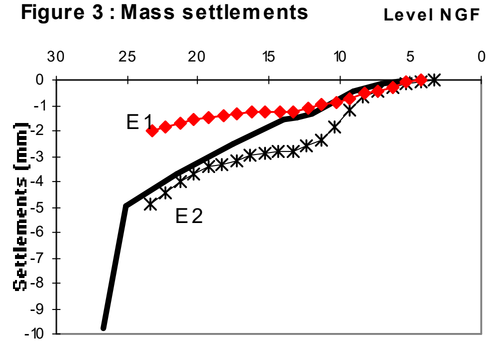
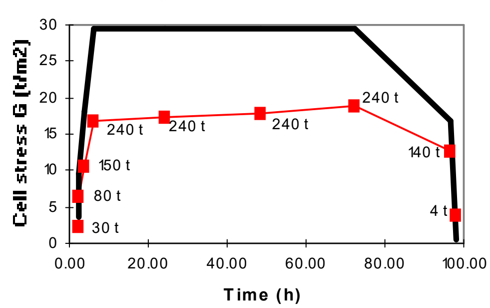


Figure 4 : Cell stress



Direct loading on column 202

Column 202 was subjected to a direct load test. The embankment was removed and to allow a direct loading to be applied, a pile cap was constructed on the column between levels 24.35 and 22.65 NGF. The loading program and the settlements at the head are given in table 4.

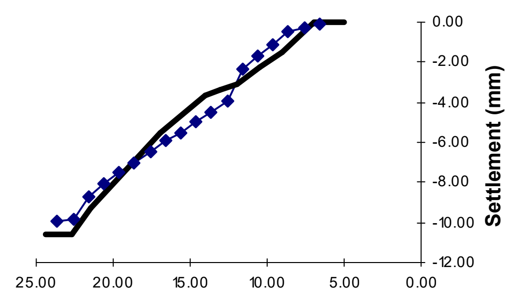
Load (MN)	Stage (min)	Level NGF	w level (mm)	w comp (mm)
0.90	5	24.347	2.49	2.49
	60			2.69
1.12	5			3.59
	60			3.81
	1200	24.372	5.04	4.21
1.32	5	24.371	5.64	4.78
	60			4.93
1.55	5			5.92
	60			6.33
1.77	5			7.36
	60			8.12
	430	24.367	9.64	8.83
	1365	24.366	10.34	9.62
1.77	7020	24.366	11.06	10.36
2.00	5			11.25
	60			11.67
2.22	5			12.89
	60			14.87

Table 4 : Direct loading on column 202

The column failed 4 minutes after the application of load from 2.22 to 2.41MN. The corresponding failure stress (4.22MPa) is greater than the average compressive resistance of the mortar in the recent alluvium (2.99MPa) and close to the maximum value (4.50MPa).

The distribution of the settlements with depth can be measured with the aid of extensometer E1, the end of the stage with a load of 177 tonnes is presented in the figure 5.

Figure 5 : Loading on column 202



CONCLUSION

The results of the tests at the A14 have confirmed that the mortar characteristics are closely linked to the parent soil. The approximate values of the maximum characteristic resistance that can be expected are :

- sands and gravels	5.0MPa
- silts	2.5MPa
- clays	1.7MPa

With an identical binder grout, the modulus of elasticity of the mortar of soil is strongly dependent on the nature of soil. For the estimation of settlements, in the range of resistance of 2 to 5MPa, the modulus to take into account can be estimated as 750 times the compressive resistance. This is the rule used in the behavioural model.

Comparison of the results of calculations using the "flexible inclusion" model with the test measurements from the A14 shows that the model gives valid predictions of the global settlements of the reinforced mass, the form of load distribution and the relative displacements between the inclusion and the reinforced mass.