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Conventional Resort to Groundwater Recharge Near Deep Excavations and Its Frequent Fallacies.

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ABSTRACT: Deep urban excavations with dewatering were conventionally analysed with regard to Factors of Safety against (rigid-plastic) failure, satisfactorily employing the classical simplification of early Soil Mechanics, of the equivalence of Total Body Forces with Boundary Neutral Pressures in lieu of the (slightly more complicated) vectorial composition of Gravity and Seepage Effective Stresses. This equivalence loses global validity except when the simplifying idealizations are fully met, thus generating significant fallacies in many design analyses, where limiting deformations are the crucial criterion, as is the case in most urban excavations. Principal analyses, professionally employed over three decades by rudimentary separate flownet and deformation calculations, are presently submitted and discussed as resulting from comparative analyses by finite differences.

1 - INTRODUCTION

Over the past thirty years roughly, conventional geotechnique has been immeasurably benefited by the advances of techniques and programs of numerical computations, coupled with the collateral evolutions of methods of analyses of continua, and even discontinuous media, via finite differences, finite elements, boundary elements, etc... Unfortunately, however, in-depth advances have been accompanied by deepening compartmentalizations within the desired, and sorely needed, global end-product, professional geotechnical engineering. Enthusiasms and production concentrate separately along multiple lanes, such as, in (a) laboratory research refinements, (b) in situ tests, (c) reinforcement and ground treatment techniques, (d) proliferation of descriptive case histories, void of generalizable lessons, (e) theorizations (few, and principally along constitutive equation idealizations), (f) numerical analysis creative manoeuvres, (g) etc...

Meanwhile, the professional solutions dominantly cling to the erstwhile proposals, and the schism between "Stability Calculations" via the Statics of Isolated "Solid" (not necessarily rigid) Masses, and Deformability Calculations within idealized media, has only grown, abetted by improved computation ability. The idealizations needed, and creatively used, four to six decades ago have not been submitted to reappraisals, nor to any effort at unification of the two conditions: (a) pre-failure deformations and their allowable limits; (b) failure analyses and the use of factors of safety.

The pungent need is felt, to use an important professional problem, not only: to discuss the errors in results that should impose revision in a solution still considered conventional and left unquestioned, but also, to demonstrate via such a practical problem the principles behind the erstwhile idealization in stability computations. This second aim, more general, is justified with a view to opening a reasoning and method for beginning systematic correlations to retrieve the countless cases of experience from designs previously conducted only on the basis of Factors of Safety FS against failure, with deformations merely inferred qualitatively.

2. PRACTICAL PROBLEM USED: groundwater recharge to control surface settlements adjacent to deep excavations.

The problem is of crucial importance in urban excavations, principally within the prospective "failure wedge", because of the risks of damage to utilities that run underground of side-walks.

The classic paper by Parsons, 1961, appropriately maintained the constant water level (and greatest proportion of the flownet) for areas and buildings somewhat distant, outside the prospective "failure wedge". But subsequent cases persist in which no distinction is made between the immediately

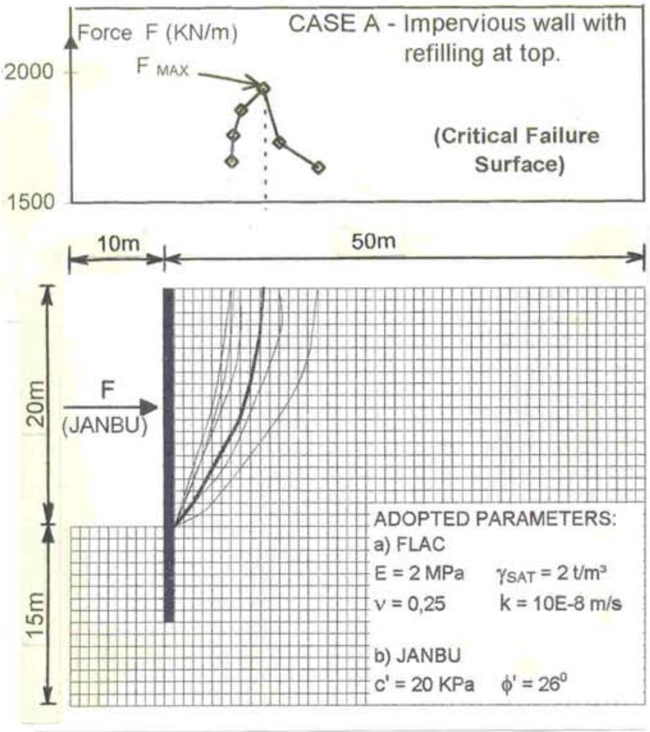

Fig. 1 - Mesh for FLAC (ITASCA,1995) and sliding surfaces (Janbu, 1954).

contiguous area, and the more distant subsoil and overlying construction. The reasoning has often been submitted that by recharging the groundwater level to the point that its depression is avoided, the desired exclusion of settlements is achieved.

The idealized case and the mesh used in the numerical analyses is presented in Fig.1, comprising a diaphragm-wall supporting a deep excavation. A recognized 2-dimensional finite difference code was used for analyses. For simplicity and comparisons, the wall is kept horizontally immovable. Such collateral arbitrary decisions are emphasized as not influencing the scope, strictly comparative, of the present work.

The problem includes on the one hand the choice of "pervious" vs. "impervious" diaphragm wall, and correspondingly the difference of seepage flownets, and the obvious differences in flows, a quite secondary consideration. Incidentally, for the horizontal water table case, independent flownets were drawn "by hand" and by computer program, with absolute similarity of results, of nets and flows. It confirms the repeated observation, easily justifiable, that in such solutions involving integration effects within continua, if the boundary conditions are respected, the needs for computer numerical precisions become irrelevant. Fig. 2 summarizes one condition among those analysed systematically.

For the transient conditions of a gradually, lowering phreatic-source the respective flownets were drawn by hand, sufficiently appropriate for the desired comparisons of the two principal aspects: stability, reflected in values of the wall reaction; and surface settlements of the soil contiguous to the walls. The groundwater recharging, sufficient to maintain the horizontal water table, has been applied both by a refilling at the top, and alternately by pumping in at the bottom. (cf. Fig. 5)

The table of flows to be pumped (table, Fig. 4) shows the practical irrelevance, especially if one realizes that the compressions and settlements would be of greater interest in the more clayey materials, simultaneously less pervious as the worrisome compressibilities increase.

In due consideration of the absolute similarity of results achieved by hand-drawn and computed of progressively lowering water surface have been

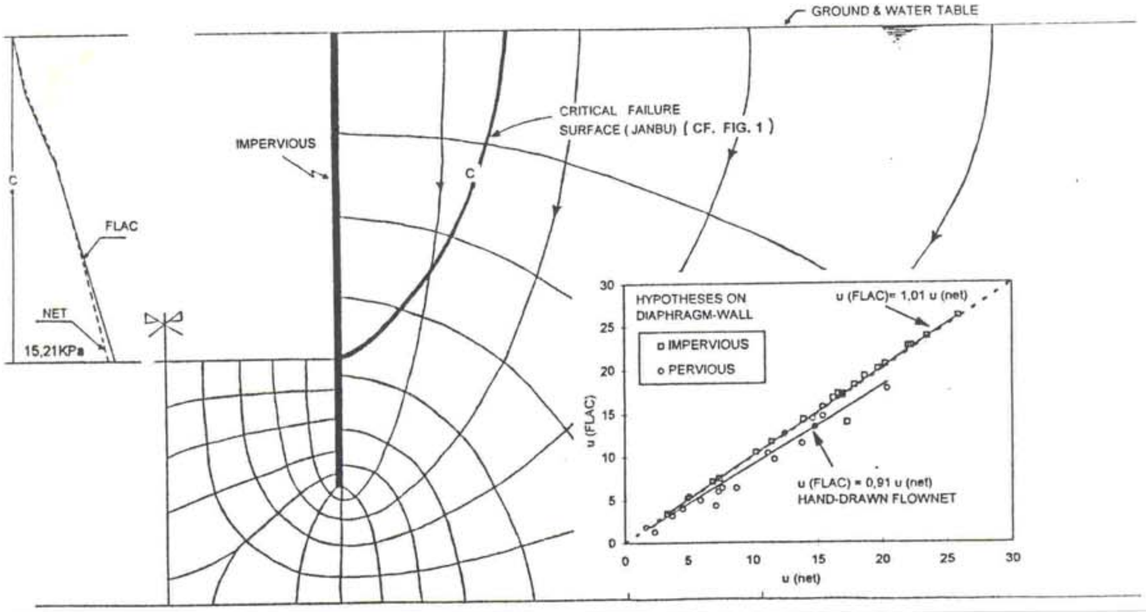

Fig. 2 - Example of hand-drawn flownet. Comparison of pore pressure with those determined by computer.

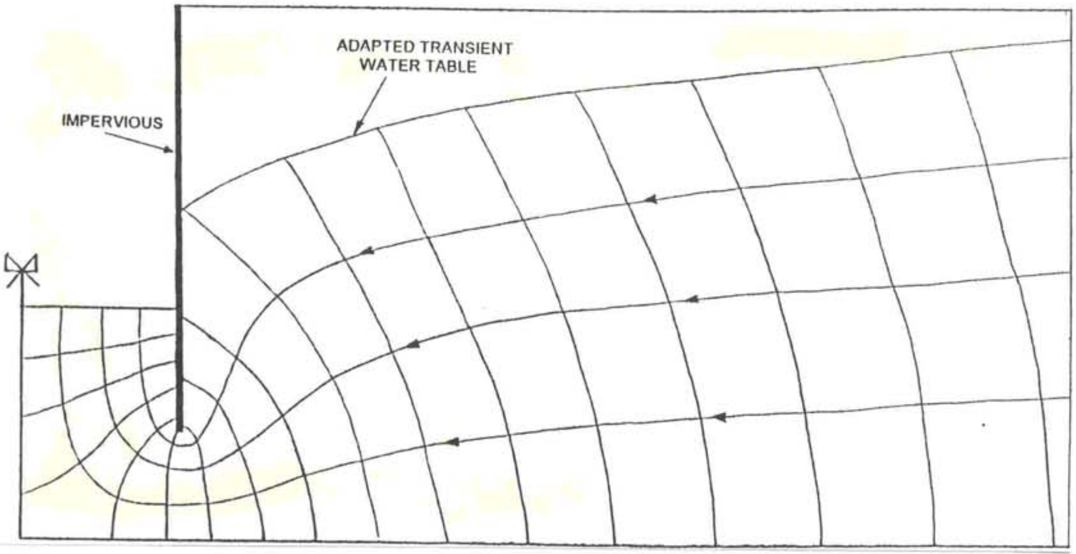

Fig. 3 - Example of hand-drawn partly drained flownet. Deformations and pressures by numerical analyses.

drawn, adopting an arbitrary moment in the process. The numerical computation does not reach a stop in such a case. Fig. 3 illustrates such a transient flownet with impervious wall.

Finally figure 4 represents a flownet condition caused by an idealized groundwater recharging by flow forces upwards to the groundwater table, at surface, as a "sink". Note that the recharging pressure was carefully adjusted by iterative trials until the pore pressure at the top reached essentially the zero value representing the "surface sink", with minimum surface runoff. With higher recharging pressures the flow vectors become more vertical and heaving, the surface sink runoff condition preserved notwithstanding.

3. PRINCIPAL QUESTIONS AT STAKE: Stability, represented as the Earth+Water Pressure Horizontal Reaction exerted by the wall to support the potential failure wedge; and Surface Settlements.

The question of destabilization of the excavation bottom is set aside as a separate problem, not broached in this paper, although very important.

The practical question of great moment is, for any of the flownet conditions, the comparison of the two separate (unfortunately still separate) analyses of pressures supported by the wall as per sliding failure analyses, and the Deformations caused within the soil mass, as computed by numerical analyses, employing vectorially integrated effective stresses throughout, both the gravity ones of submerged specific weight, and those of flownet-directed seepage stresses.

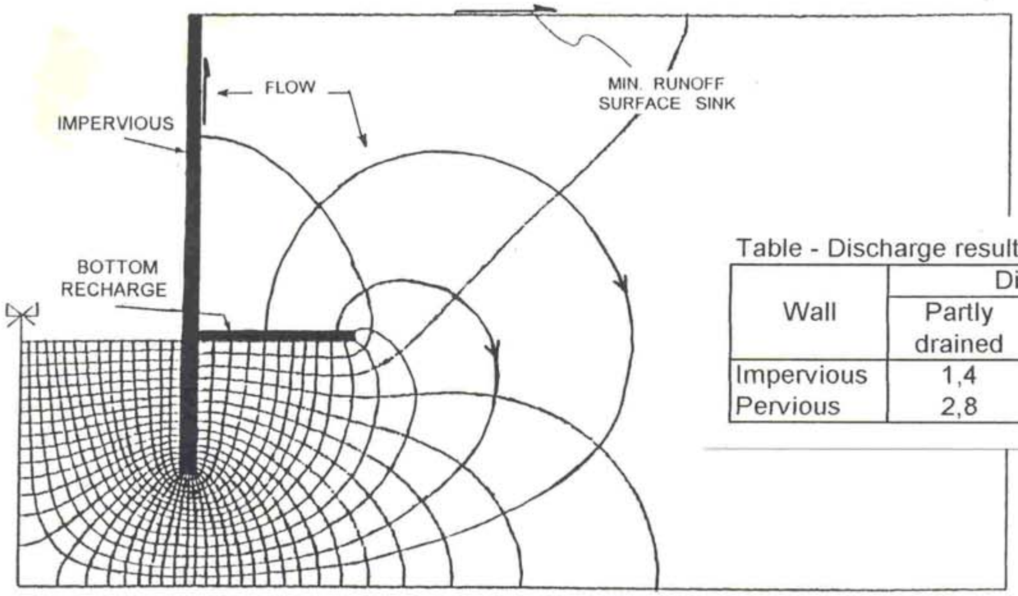

Table - Discharge results.

Wall	Discharge (l/h.m)		
	Partly drained	Refilling at top	Bottom recharge
Impervious	1,4	2,4	4,8
Pervious	2,8	5,7	-

Fig. 4 - Example of bottom recharge flownet.

The desire in this paper is to reestablish fundamental principles, and, thereupon, the convincing practical suggestions of great consequence, as well as the indications on the computational routines to be respected in professional problems. For the sake of clarity of comparisons some simplifications and idealizations of secondary importance have been used. Attention was restricted to hypothetical failure surfaces cutting across the wall at the bottom of its free height, so that attention be focused on the conditions of the adjacent retained soil mass.

3.1 *Destabilization, Active Earth Force, and Resisting Force of Wall.*

Stability analyses were performed by computer program for the Janbu generalized failure surface, but with the simplification of disregarding side forces on the slices, very commonly taken, unquestioned, as sufficient. Mention of Rankine, and even Coulomb, analyses is set aside as unquestionably inapplicable to the case. The wall pressure was purposely adopted as horizontal in order to avoid eventual spurious effects (vertical) on the soil mass. The analyses follow the undisputed routine of static equilibrium of the isolated body as per total weights together with boundary forces[1]. In the case of lowered water table, capillarity was taken as zero, but no change of specific weight included. The critical sliding surface (for active earth-pressure condition, wall fixed) was determined for each groundwater condition and is shown in Fig. 1 for impervious wall with top refilling.

The concept is herein accepted as dogmatic that the statics of an isolated body x.y.z as established by the equilibria $\sum x = 0$, $\sum y = 0$, $\sum z = 0$, $\sum M_{all} = 0$ prevail unchanged independently of small changes of shape and volumes (weights)[2]. In a companion paper we shall pursue the demonstration of the manoeuvres for optimizedly transforming the vectorial mass effective stresses in the continuum, into total stresses in the body and separate boundary stresses so as to demonstrate this conceptual compatibility in practical terms. It will be of use in summarizing a considerable series of typical cases conventionally designed via FS on failure analyses, into the nowadays progressively more desired stress-deformation finite element analyses: it is indispensable that such a well-documented transfer be facilitated from past dominant practice and experience, into the inexorable trend, improved and more fertile for increasingly needed collateral decisions on allowable deformations and FS.

Profiting of the above accepted and proven equivalence, and of the greater credibility and facility provided by the numerical computations, the remainder of our present results were by the sequence of analyses in terms of (mass) vectorial effective stresses, undisputably "correct" by fundamental principles.

3.2 *Comparative wall pressures, and settlements of the retained soil mass surface.*

The isolated solid body is not rigid: it is taken as (merely) elastic, with a very low modulus, since the groundwater recharging would be principally considered in such very deformable conditions, and the purposeful idealized magnification of pre-failure deformations favours comparisons.

The modulus that appears applicable to the desired settlement computation, however, would be that of the undrained compressibility of saturated soil (cf. Bishop 1973, Bishop and Hight 1977), comparatively so high that settlement calculations of slices within the stability wedge become irrelevant.

The four cases considered have the flownet boundary conditions as schematically illustrated in Fig. 5 representing :

A. Groundwater recharged at surface, imperv. wall.
B. Idem, pervious wall.
C. Groundwater partly drained, impervious wall.
D. Groundwater recharged to original level by injecting water at base, upward seepage effective stresses, impervious wall.

In figure 6 we present graphically the results of principal interest which are:

a. Earth pressure force against the vertical face, to be compared with the critical value (active earth pressure), cf. Table 1.

b. Total force (earth+water pressure) to be resisted by the wall.

The results speak for themselves. The differences of pressures against the wall are not minor, and significantly affect economy, but in principle can be accomodated without having to change the condition of zero lateral displacement.

As regards the protection against settlements, the benefit at greater distances is undisputable and obvious. However, within the wedge one must seriously guard against the fallacious expectation of the benefit merely because water table is maintained high. The settlements due to compression of the soil continue to be high, in the case of the groundwater simply recharged from above. The significant benefit is achieved by use of groundwater recharge from below, by upward seepage. Note, however, that the

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[1] On the sliding surface these being taken as resulting from geostatic stresses with no eventual influence from hypothetical internal residual stresses in the soil.

[2] Effects of stress redistributions in surfaces, coupled with significantly non-linear strength equations are left quite beyond the present scope.

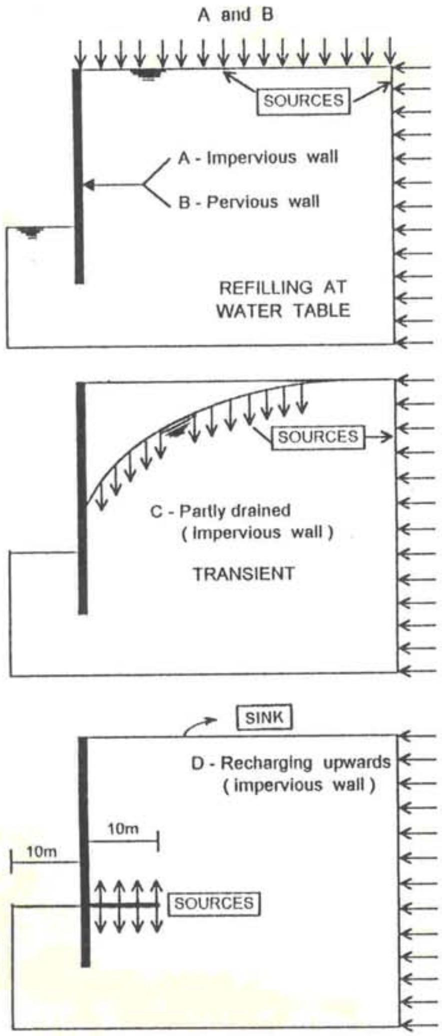

Fig. 5 - Significantly different source-sink conditions of possible flownets.

nominal moduli of elasticities, of compression and decompression, must be judiciously evaluated, or even considered immaterial, if the iterative adjustment between tendencies to compression and expansion chances to be especially synchronizable.

Since the maintenance of constant water table had been associated with control of settlements, as a first step we plot in Fig. 7 the results of the settlements as determined by numerical computations, for the four conditions of mass effective stresses influenced by vectorial seepage effective stresses previously mentioned. The efficacy is clearly demonstrated, and easily justified, as only derivable from upward seepage stresses by recharging from below. For one condition (case A) the comparative computation was attempted via the concept of total stresses with boundary pressures. For the sake of fair comparison the stresses were taken from the numerical computations and transformed into the idealized conventional concept: the settlements (vertical compressions) were computed for individual "slices". Using the Bishop and Hight, 1977 undrained modulus as roughly 4000 MPa (40000kg/cm^2), the computation yields a very low vertical compression, showing that deformations also cannot be supported on the conventional idealization of routine use in

Table 1. Comparative results of earth forces and total wall reactions.

Condition	Earth forces	(KN/m)	FS
A) Imperv. wall	JANBU:	1940	1.00
Refilling at top	FLAC:	1350	1.44(2)
B) Pervious wall	JANBU:	1110	1.00
Refilling at top	FLAC:	1407	0.79(1)
D) Imperv. wall.	JANBU:	2230	1.00
Bottom recharg.	FLAC:	933	2.39(2)

Total wall reactions.

Condition	(KN/m)		FS
A) Imperv. wall	JANBU:	3460	1.00
Refilling at top		3940	0.88(3)
	FLAC:	2947	1.17(2)
B) Pervious wall	JANBU:	2100	1.00
Refilling at top		3110	0.68(3)
	FLAC:	2393	0.88(1)
D) Imperv. wall	JANBU:	4350	1.00
Bottom		4230	1.03(3)
recharging	FLAC:	3054	1.42(2)

(1) Unacceptable results, since the numerical condition was not imposed to reach failure, drawing on full resistance capacities of the soil sliding surface: demonstrates a condition wherein invalidity of computational idealization for destabilization is salient.

(2) Demonstrating a condition wherein the above invalidity is so significantly attenuated as to have permitted conventional destabilization calculations to have been very frequently within reasonable range. The example used was purposely directed towards exaggerating the incorrect effects.

(3) Assuming hydrostatic pore pressures.

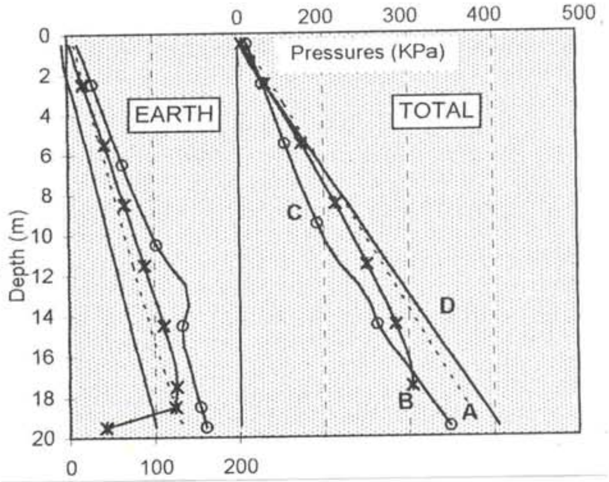

Fig. 6 - Earth pressures and total wall reactions.

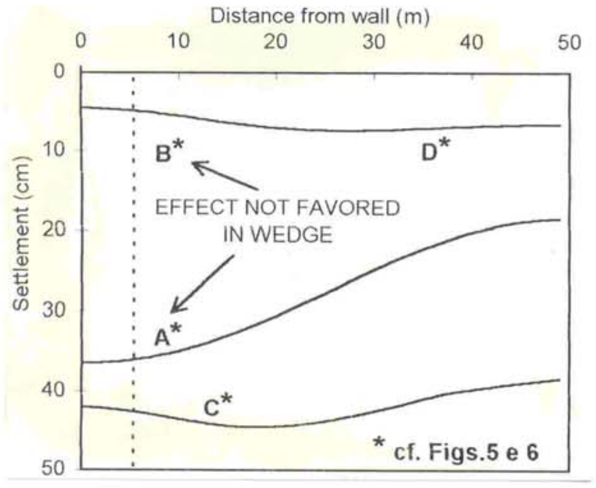

Fig. 7 - Settlements calculated by numerical analysis.

destabilization calculations.

Regarding the earth and total pressures exerted on the wall, table 1 gives the comparative results, for the groundwater table maintained at the surface. Since the Janbu-type calculation is presumed to give the (critical) Active Earth Pressure (i.e. the failure condition, FS= 1,0) the different forces are expressed as proportions to the values of the Janbu (simplified) analysis. The importance of the vectorial mass forces of seepage effective stresses is clearly shown by comparing, for instance, the PERVIOUS vs. IMPERVIOUS wall: in the former the seepage stresses add much more of horizontal body forces, while in the latter, with seepage obliged to be much more subvertical within the soil wedge, the flownet does not affect the horizontal stress.

Fig. 8 exposes the conflicting effects on the two principal design results, retaining forces and compression settlements. Improved realism of analyses and judicious design optimizations are a must. For the specific case computed, the pervious wall offers by far the best combination.

4. CONCLUSIONS

4.1. Both for destabilizations, and for settlements, the only acceptable computational methods must be those based on mass effective stresses vectorially composed.

4.2. Considering the voluminous experience of designs employing destabilization calculations employing the simplifying idealization, it is recommended that for a sufficient transition period, computations be conducted concomitantly by BOTH METHODS, to establish correlations between conventional computations and desired realistic ones.

4.3. The great importance of flownets, and not merely boundary neutral pressures, is shown. The effects reflect heavily on the wall pressures and surface settlements. As regards these, the conventional destabilization computations do not give any foreseeable means of calculating deformations associated with conventional FS.

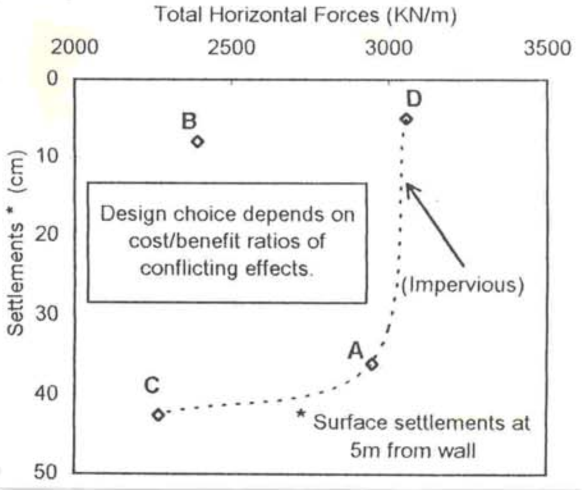

Fig. 8 - Conflicting effects influencing design decisions, for optimizing.

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