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Behaviour of Combined Piled Raft Foundation in Clayey Soil

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***Abstract*-In situations where a raft foundation alone does not satisfy the design requirements, it may be possible to enhance the performance of the raft by addition of piles, the use of a limited number of piles, strategically located, may improve both the ultimate load capacity and the settlement and the differential settlement performance of raft. This paper discusses the philosophy of using piles as settlement reducers and considering interaction effects. In this method the raft is considered as a plate supported by a group of piles. To verify the reliability of the proposed method, a 5 storied RCC structure is analysed in SAP 2000, considering the guidelines given in chapter 56 of ICE manual of geotechnical engineering (volumeII) and Theoretical manual for pile foundation by US Army corps of Engineers (ERDC/ITL TR-00-5).**

***Keywords*- Pile, Raft, Piledraft, Pile enhanced raft, Raft enhanced pile group, Compensated raft, SAP 2000.**

I.INTRODUCTION

The piled raft foundation system has recently been widely used for many structures, especially high-rise buildings. In this foundation, the piles play an important role in settlement and differential settlement reduction, and thus can lead to economical design without compromising the safety of the structure.

1. Raft Foundation: It is a large slab supporting a number of columns and walls under entire structure or a large part of the structure. The four main reasons for using raft foundations are:
The individual excavations for numerous pad or strip footings are relatively close to one another, and for construction purposes it is easier to create a single large excavation.
The differential settlement between individual footings is excessive, and the use of a relatively rigid raft is needed to minimise differential settlement to a tolerable value.
There is a reduced risk of damaging differential settlements in heterogeneous ground conditions.
There is a reduced risk of bearing-capacity failure and excessive settlement or differential settlement through using cellular rafts in soft clays.

2. Pile Foundation: Pile foundation, a kind of deep foundation, is actually a slender column or long cylinder made of materials such as concrete or steel which are used to support the structure and transfer the load at desired depth either by end bearing or skin friction. Pile foundation are often used because there is a concern about excessive settlement of shallow foundations, even though a raft would have an acceptable factor of safety (FOS) against bearing-capacity failure. Conventional design of the pile group would then ignore the resistance provided by the pile cap or raft, and solely consider the resistance provided by the piles; i.e., all the design load is transferred through the piles.

3. Piled Raft Foundation: In pile raft foundation, piles provide support to control settlement and the raft delivers additional capacity at ultimate loading, which reduces the required number of piles. Raft may provide redundancy to the piles and thus reduces the potential influence of affected piles (if any) on the foundation performance. In this situation, the raft allows redistribution of the load from the affected piles to those that are not affected. Piles also reduce the differential settlement when the raft alone exceeds the allowable settlement. The raft may increase the lateral stress between the underlying piles and the soil, and thus can increase the ultimate load capacity of the pile compared to free-standing piles.

II. DIFFERENT TYPES OF PILED RAFT FOUNDATION

1. Raft Enhanced Pile Group:
Both the piles and the raft will work within a pseudo-elastic range of behaviour. The pile group capacity will not fully be mobilised at the anticipated working load. The key parameter that governs behaviour is the relative stiffness of the pile group to the raft. It will be important to assess the upper and lower bound stiffnesses for the raft and pile group. Although the piles will usually be stiffer than the raft and attract most of the design load, the raft can be designed to resist a substantial proportion of the design load.

2. Pile Enhanced Raft:

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The piles will be designed to mobilise all their ultimate capacity. The raft will usually carry the bulk of the design load. The piles will usually be located beneath heavily loaded superstructure columns. For this type of design, it will be important to assess both the lower and upper bound pile capacity with a high level of confidence, and the pile load-settlement behaviour must be ductile, i.e. the pile resistance must be maintained at relatively large settlements.

2.1Load settlement behaviour of rafts, conventional pile group and different types of piled raft:

The figure.1 shows a load-settlement curve for a raft (curve 1), a conventionally designed pile group (curve 2), a raft- enhanced pile group (curve 3) and a pile-enhanced raft (curve 4). The raft has a substantial ultimate bearing capacity, but the settlement at working load is deemed to be excessive. The conventionally designed pile group is very stiff and its settlement at the working load is far smaller than the 'allowable' settlement. The raft-enhanced pile group (curve 3) is also relatively stiff and this is achieved with a smaller number of piles than the conventionally designed pile group, because the piles are operating more efficiently. The pile-enhanced raft (curve4) exhibits more settlement than the conventional pile group and raft enhanced pile group, but is stiffer than the raft and can achieve the allowable settlement for this structure. The load-settlement curve for the pile-enhanced raft is within the nonlinear range.

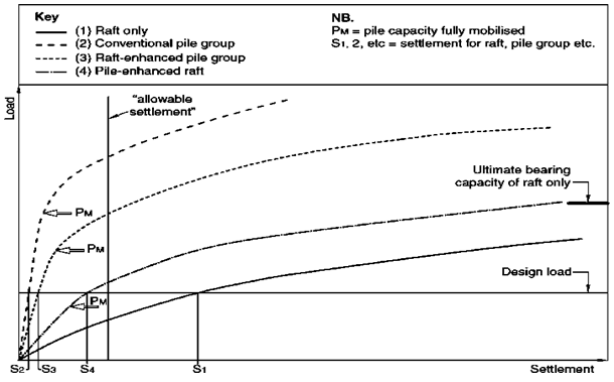

Fig 1. Load settlement behaviour of rafts, conventional pile group and different types of piled raft.

2.2Pile enhanced raft versus raft enhanced pile groups:

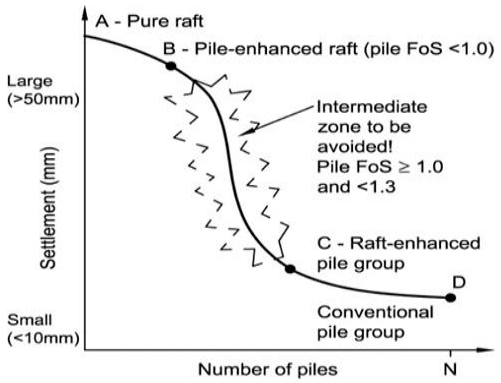

Fig 2. Pile enhanced raft versus raft enhanced pile groups.

A clear distinction must be drawn between raft-enhanced pile groups and pile-enhanced rafts. The design concepts and methods are very different. As shown in figure above, there is an intermediate zone between a raft-enhanced pile group and a pile-enhanced raft, which should be avoided. If it isn't avoided, with the wide range of load cases, it is entirely possible that one column will feel a soft response while a neighbouring column may experience a stiff response, setting up large differential displacements in the building.

3. Compensated Raft:

Raft designed as a deep box with the void within the raft reducing the net increase in bearing pressure. The net pressure on the foundation soil is further reduced by higher embedment depth and simultaneous construction of a base wall. In this case the excavated soil is not used further as a backfill which aids in significant reduction of overburden pressure. The weight of the structure is partially or fully compensated by the weight of excavated soil and hence provides a reduction in the subsequent settlement.

III. PILE RAFT INTERACTION

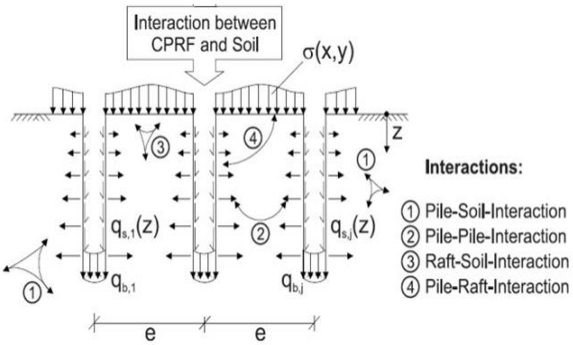

Fig 3. Pile Raft Interaction.

Following interactions are considered in the analysis of combined piled raft foundation as shown in the figure above,

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1. **Raft–Soil Interaction:** The contact stresses between the raft and the soil are transmitted into the soil and settlement of the raft takes place.
2. **Pile–Soil Interaction:** The pile loads disperse into the ground surrounding the piles.
3. **Pile–Pile Interaction:** Interaction takes place between each pile through the soil to other piles.
4. **Pile–Soil:** Pile interaction will occur when the piles are spaced at less than about 6d to 8d (d = pile diameter). If the pile spacing is greater than 8d then the pile-to-pile interaction will be negligible.
5. **Pile–Raft Interaction:** Interaction takes place between each pile through the soil to the underside of the raf

$$K_{Hb} = \left(1 + 0.21\left(\frac{D_r}{L_r}\right)^{0.50}\right) E_s L_r$$

IV. LE RAFT INTERACTION

1. Raft–Soil Interaction:
Piles are considered to be connected rigidly with raft foundation. A square raft is modelled using four noded shell elements discretised into square meshes. Each node of the shell is considered to have three degrees of freedom (two in mutually perpendicular horizontal directions and one in the vertical direction).

Raft soil interaction is modelled using distributed linear springs connected below the entire raft area. The stiffness of an embedded raft is considered as consisting of two components, one due to the interaction between the base of the raft and the underlying soil and the other due to the interaction between the sides of the raft and the surrounding soil. These two stiffness components are added to give the overall stiffness of the raft foundation, as per Gazetas.

$$K_{\text{embedded raft}} = K_{\text{base}} + K_{\text{sidewalls}}$$

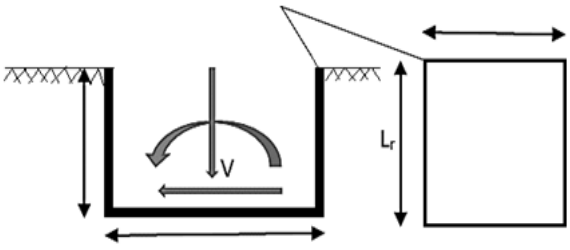

Fig 4. Rigid raft/basement structure.

1.1 Static analysis:
1.1.1Vertical stiffness
The vertical stiffness of raft is given by,

$$K_{Vb} = 1.51\left(1 + 4.67\left(\frac{D_r}{L_r}\right)\right) E_s L_r$$

Where,
Es = young's modulus of the soil
Dr = depth of the raft
Lr = length(=breadth) of the foundation.

The vertical stiffness contribution from complete sidewall contact,

$$K_{Vsw} = 0.48\left(\frac{D_r}{L_r}\right)^{0.67} K_{Vb}$$

1.1.2 Horizontal stiffness:
The horizontal stiffness of the base of the raft,

The horizontal stiffness contribution from the sides of the raft,

$$K_{Hsw} = 1.58\left(\frac{D_r}{L_r}\right)^{0.80} K_{Hb}$$

1.2 Dynamic analysis:
Soil is idealized as equivalent springs that are located at the centroid of the foundation in each degree of freedom. The stiffness of equivalent springs are as follows (Gazetas 1991).

Stiffness of equivalent springs along various degree of freedom. (Gazetas 1991)

Degrees of freedom	Stiffness of equivalent soil spring
Vertical (K_v)	$(2GL_R / (1 - \nu))\ (0.73 + 1.5\chi^{0.75})$
Horizontal (K_{xG1}) (lateral direction)	$(2GL_R / (2 - \nu))\ (2 + 2.54\chi^{0.85})$
Horizontal (K_{xG2}) (longitudinal direction)	$(2GL_R (1 - \nu))\ (0.73 + 1.54\ \chi^{0.75} - (0.2(0.75 - V)\ GL_R(1 - (B / L_R))$

Where: χ = Ab / 4L 2, Ab is the area of the foundation; B and LR are half width and half-length of a rectangular foundation, respectively; G is shear modulus of soil and ν is the poisson's ratio of soil.

2. Modelling of Pile Soil Interaction:
Soil is idealized using Winkler's springs to simulate the soil-pile interaction effects which is idealized in terms of following curves:

- **p-y curves:** These represent the variation of soil pressure with lateral displacement of pile.
- **t-z curves:** These represent the variation of skin friction at pile-soil interface with the relative axial displacement of pile with respect to soil.
- **q-z curves:** These represent the variation of tip pressure with axial displacement of pile tip.

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- All the above are estimated based on the type of soil layer based on US Army Corps of Engineers, ERDC/ITL/TR- 00-5, 2000.

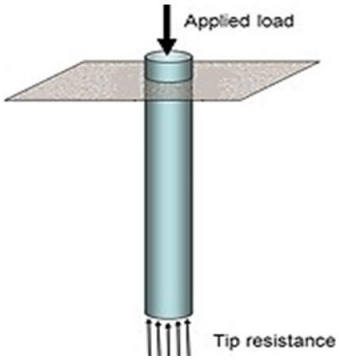

Fig 5. Pile under vertical load

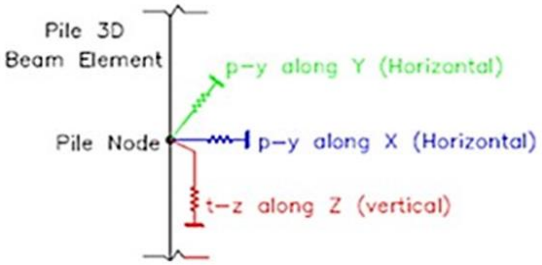

Fig 6. 3D pile element

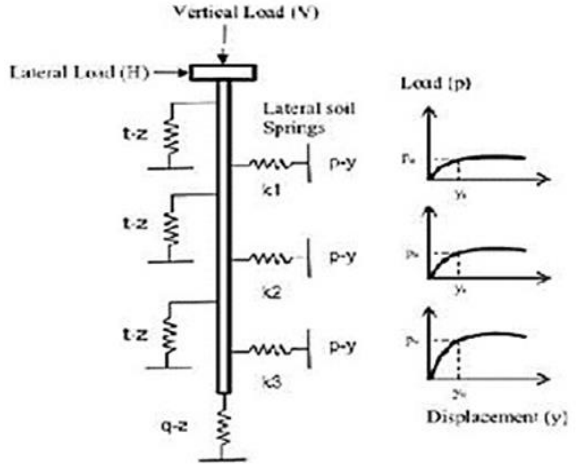

Fig 7. p-y and t-z curvesunder vertical and lateral load

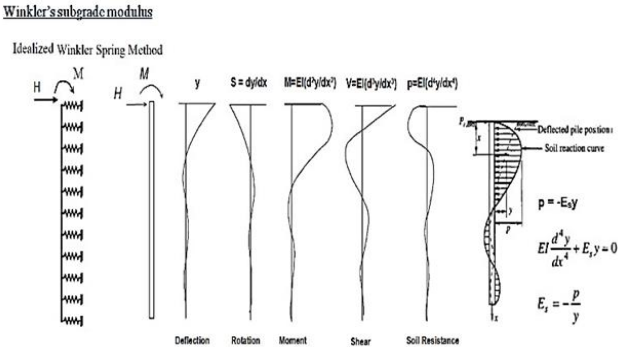

Fig 8. Idealized winkler spring

2.1 Static Analysis (IS:2911 part-1 section 2:2010):
As per the borehole data soil at the site is classified as clay.

2.1.1 p-y curves:
$p/y = \eta_h.z$ where,
p = lateral soil reaction per unit length of the pile at depth z below ground level.
y = lateral pile deflection and ηh = modulus of subgrade reaction.
The lateral soil resistance for preloaded clays with constant soil modulus is modelled as,

$$p/y = K$$

$$K = \frac{k_1}{1.5} \times \frac{0.3}{B}$$

Modulus of subgrade reaction for cohesive soils, k1 in kN/m^3. (IS:2911 part-1 section2:2010)

Sl No.	Soil Consistency	Unconfined Compression Strength, q_u kN/m^2	Range of k_1 kN/m^3 × 10^3
(1)	(2)	(3)	(4)
i)	Soft	25-50	4.5-9.0
ii)	Medium stiff	50-100	9.0-18.0
iii)	Stiff	100-200	18.0-36.0
iv)	Very stiff	200-400	36.0-72.0
v)	Hard	> 400	>72.0
NOTE — For q_u less than 25, k_1 may be taken as zero, which implies that there is no lateral resistance.			

2.2.2 t-z curves:
These curves are represented as t-w/f-w curves in the U.S.Army Corps of Engineers, ERDC/ITL/TR-00-5, 2000. Aschenbrener and Olson recommendation is used for estimation of t-z curves.

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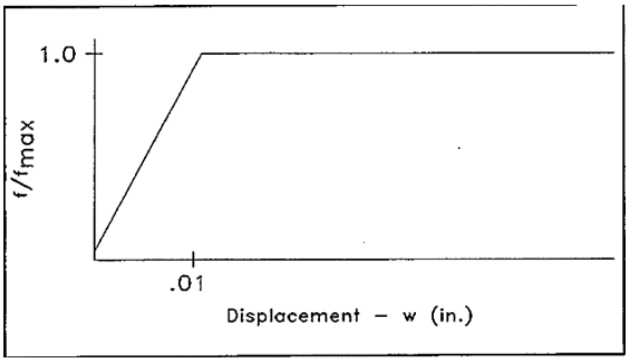

Fig 9. t-z curve (Aschenbrener and Olson)

$K_{tf} = f_{max} / 0.004D$
K_{tf} is the initial modulus of the t-z curve which remains constant up to δv = 0.004D (silva (2008)) beyond which t-z becomes constant at fmax.
fmax (maximum mobilised shear stress) = α.Su.
su = undrained shear strength of soil.

$$\alpha = \frac{(P_{ou} - P_{tu})}{s_u A_s}$$

This t-z curve is used in both static & dynamic analysis

2.2.3 Curves for bearing in soil:
For piles bearing in rock, the tip reaction–tip displacement relationship is assumed as linear. The equation given by Kraft, Ray and Kagawa is used for estimation of q-z curves.

$$w = \frac{2Rq\,(1 - \nu^2)}{E} I_t$$

$$= q.(1/k_{qwz})$$

Where,
w = tip displacement in m, q = tip pressure in KN/m^2,
R = radius of pile tip reaction = D/2.
For dynamic analysis E_{dyn} value is used.

2.2 Dynamic analysis:
2.2.1 p-y curves:
A series of lateral load tests on instrumented piles in clay (Matlock 1970) were used to produce the p-y relationship for piles in soft to medium clays subjected to static lateral loads.

$$\frac{p}{p_u} = 0.5 \left(\frac{u}{u_c}\right)^{1/3}$$

$$u_c = 2.5\epsilon_{50} b$$

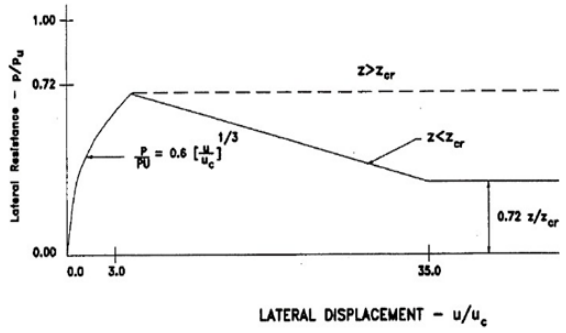

Fig 10. p-y relation (Matlock 1970)

As suggested by Edmonds (1980), the elastic soil stiffness for dynamic analysis should relate to the secant stiffness of the p-y curve at approximately one-half of the ultimate lateral soil resistance.

Therefore, the modulus of subgrade reaction is given by,
$k = 0.5P_u / u_c$
P_u = ultimate lateralresistance.
$P_u = N_p \times c_z \times D$
N_p= normalised ultimate soil resistance
u_c = lateral displacement at one-half of the ultimate resistance.
ε_{50} = strain at 50% of the ultimate strength from a laboratory stress – strain curve. (Typical values of ε_{50} are as per table 3 of ERDC/ITL/TR-00-5,2000).

3. Pile-Soil-Pile interaction effect is also considered for lateral and vertical loading.
The following efficiency factors for pile groups are considered:

3.1 Interaction for lateral loading: This is estimated based on the recommendations of FEMA P-751, 2012.
Based on full-scale testing and subsequent analysis, Rollins et al. recommend the following multipliers(fm), where D is the pile diameter or width and s is the center-to-center spacing between rows of piles in the direction of loading.

First (leading) row piles: $f_m = 0.26\ln\left(s/D\right) + 0.5 \le 1.0$

Second row piles: $f_m = 0.52\ln\left(s/D\right) \le 1.0$

Third or higher row piles: $f_m = 0.60\ln\left(s/D\right) - 0.25 \le 1.0$

3.2 Interaction for vertical loading: This is estimated based on the recommendations of Novak (1991).
Novak and Grigg (1976) suggested interaction factor αa as a function of pile length and spacing for piles in a group.

4. Modelling of Piled Raft Interaction:

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Pile raft interaction factor is estimated as follows,

$$\alpha_{cp} = 1 - \frac{\ln(r_c/r_0)}{\zeta}$$

Where,
α_{cp} = raft – pile interaction factor
r = average radius of pile cap (corresponding to an area equal to the raft area divided by number of piles)
r_0= radius of pile
$\zeta = \ln(r_m / r_0)$
r_m= = 0.25ρ * (1-ν) * L
ρ = degree of homogeneity of the soil = E_{sav}/E_{sl}
E_{sav}= average soil young's modulus along pile shaft
E_{sl} = soil young's modulus at level of pile tip
ν = poisons ratio.

5. Modelling of Super structure:
Two-noded elastic-prismatic 3-D beam elements have been used for modelling beams and columns. Four-noded (rectangular) thin shell elements have been used for modelling planer RC components of building such as roof slabs, RCC walls, staircase waist slabs and landings.

6. Detailed representation of finite element model for soil raft and soil pile system:

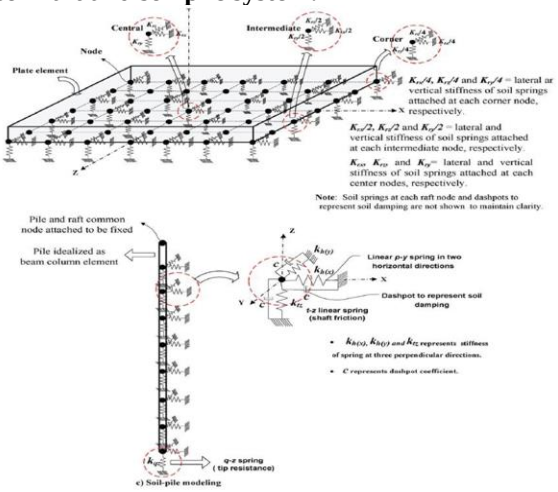

Fig 11. Finite element model representation of raft and pile

7. Finite element model of the building with piled raft foundation.

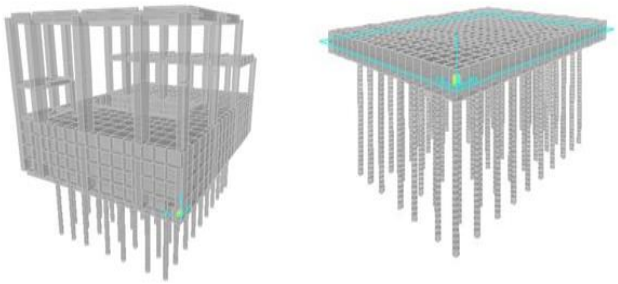

Fig 12. Finite element model of the building with piled raft

V. RESULTS AND DISCUSSIONS

Properties of soil: Young's modulus = 23.6Mpa;
Poisson's ratio = 0.3; Angle of internal friction (Ø) = 30;
Unit weight (γ) = 18 (kN/m^3)
Piled raft is analysed for different pile spacing and raft thickness.
The pile diameter = 600mm.
Pile spacings = 4d, 5d, 6d & 8d. (where d = pile diameter)
Raft thickness = 1000mm, 1200mm, 1500mm.

Settlement (in mm):

Settlement with only raft = 194mm (with 1000mm thick raft)					
Pile spacing		4d	5d	6d	8d
Pile diameter 600mm & Raft thickness	1000mm	55	63	99	137
	1200mm	45	53	86	126
	1500mm	37	44	72	115

Pile spacing	4d	5d	6d	8d
Pile diameter 600mm & raft 1000mm thick				
αpr	0.310	0.203	0.137	0.035
Pile FOS	0.76	0.43	0.20	0.065

VI. CONCLUSION

Average vertical settlement of piled raft increases with the decrease in number of piles.The differential settlement of a piled raft is obtained and found that an increase in raft thickness causes an increase in the rigidity of the raft, which in turn causes a decrease in the differential settlement.Interaction is negligible for pile spacing more 6d.

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