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Cost-Effective Foundation for Low-Rise Buildings

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***Abstract*: Backfilled soil on the top layer is always disregarded in foundation calculation for many low-rise buildings. the properties and depth of backfilled soil that can support the shallow foundation for the economic cost are the purpose of this research. Especially, the useful guidance is provided in choosing a suitable foundation for low-rise buildings. For methodology, first, survey at the real site is necessary point to collect useful information such as soil data and foundations, then sand is selected in backfilling due to the low cost, it's convenient to construct and to find, afterward general graphics of footing design chart for loads from 200 to 1000 *kN* are created by three influential parameters such as elastic modulus, effective internal friction angle, and compacted soil dry density, after that three construction sites from survey are applied in general graphics of footing design chart if shallow foundation is required or not, three types of sand which are often utilized in country are considered to be backfilled soil and replaced the backfilled soil at sites. Finally, the minimum cost from the comparison between deep foundation at site and shallow foundation on new backfilled soil above is considered as cost-effective foundation. For the result, shallow foundation on new backfilled soil is more effective than deep foundation for site 2 and 3, otherwise for site 1 because of not enough backfilled soil depth. In conclusion, according to the research above, two main points that shallow foundation is more effective than deep foundation are backfilled soil properties and its depth. Weak sand is the optimal choice among three types of sand above for backfilling. In this thesis, natural soil consolidation is assumed to be completed. For future work, natural soil consolidation and standard compacted soil method at in situ will be considered in order to reduce the time consolidation and get the same elastic modulus of soil as testing at laboratory for shallow foundation construction on backfilled soil at sites.**

Author keywords: Cost-effective foundation; Low-rise buildings; Economy; Three influential parameters; Backfilled soil; Soil properties.

I. INTRODUCTION

Nowadays, in Cambodia, especially in Phnom Penh city, many houses are constructed in order to respond the population growth from day to day. Low-rise buildings have been constructing to serve people's needs. Because of backfilled soil neglecting on the top layer, it causes the wasteful expenses to the deep foundation. However, some areas have too high backfilled soil depth.

II. LITERATURE REVIEW

Common ranges of soil properties

Table II.1: General range of elastic modulus of sand (Reese *et al.*, 2005):

Type	E (*kN/m²*)
Coarse and Medium Coarse Sand	
Loose	25000-35000
Medium dense	30000-40000
Dense	> 40000
Fine Sand	
Loose	20000-25000
Medium dense	25000-35000
dense	35000-40000
Sandy Silt	
Loose	8000-12000
Medium dense	10000-12000
dense	12000-15000

Table II.2: Minimum and maximum dry density of soil (Sulewska, 2010):

Type of soil	**Silty sand**	**Fine sand**	**Medium sand**
Number of patterns	21	47	24
$\rho_{d,\min}$ $[g/cm^3]$	1.253-1.569	1.247-1.578	1,320-1.632
$\rho_{d,\max}$ $[g/cm^3]$	1.643-1.849	1.604-1.903	1,701-1.869

Type of soil	**Coarse sand**	**Sand and gravel mixes**	**Gravel**
Number of patterns	13	11	5
$\rho_{d,\min}$ $[g/cm^3]$	1.458-1.746	1.612-1.881	1.591-1.773
$\rho_{d,\max}$ $[g/cm^3]$	1.751-2.019	1.850-2.112	1.982-2.124

International Journal of Engineering Research & Technology (IJERT)
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Table II.3: Some typical values of soil friction angle (Geotechdata.info, 2013):

Description	Symbol	Soil friction angle $[^\circ]$	
		min	max
Well graded sands, gravelly sands, with little or no fines	SW	33	43
Poorly graded sands, gravelly sands, with little or no fines	SP	30	39
Sand	SW, SP	37	38
Loose sand	(SW, SP)	29	30
Medium sand	(SW, SP)	30	36
Dense sand	(SW, SP)	36	41
Silty sands	SM	32	35
Silty sand - Loose	SM	27	33
Silty sand - Dense	SM	30	34

- **For general equation of general shear failure** (Scarpelli, 2013):

$$q_u = C^{'} N_c b_c s_c i_c + q^{'} N_q b_q s_q i_q + 0.5 B^{'} \gamma^{'} N_\gamma b_\gamma s_\gamma i_\gamma$$

(Drained Condition)

Where:

- b_c, b_q, b_γ : Base inclination of the foundation;
- s_c, s_q, s_γ : Shape of foundation;
- i_c, i_q, i_γ : load inclination factor;

- **Elastic settlement of sandy soil by using Strain Influence Factor**

The most famous methods to calculate elastic settlement for sandy soil is (Al-agha, 2015):

$$S_e = C_1 C_2 \left(\bar{q} - q\right) \sum_1^i \frac{I_z}{E_i} Z_i$$

Where:

- $C_1 = 1 - 0.5 \times \dfrac{q}{\bar{q} - q}$: Correction factor for depth of foundation embedment;
- $C_2 = 1 + 0.2 \times \log\left(\dfrac{Time\ in\ years}{0.1}\right)$: Correction factor to account for creep in soil;
- $\bar{q}$: Stress at the level of the foundation;
- q : Increased effective stress at the base of the foundation;
- E : Elastic modulus of soil;
- Z_i : Thickness of each soil layer;
- I_z : Influence line factor;

Table II.4: Recommendation of European Committee for Standardization on Settlement (Das, 2007):

Item	Parameter	Magnitude	Comments
Serviceable limiting value	S_T	25 *mm*	Isolated footing
		50 *mm*	Raft footing
Maximum settlement	$S_{\max}$	32 *mm*	Sand

II. METHODOLOGY

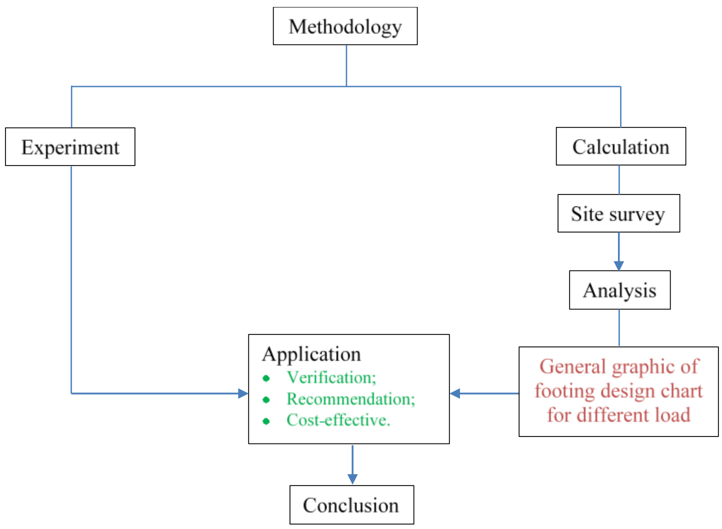

Figure III.1: Schema for thesis process

III.1 Experiment

In this chapter, three types of sandy soil are bought from sand depot, these types are often utilized in building construction and convenient to find. Weak, river, and stream sand (see figure **III.2, 3, 4**) are called by sellers and customers, procedures below are used for finding required soil parameters to design shallow foundation.

- **Sieve analysis**: define name, symbol, and soil distribution;
- **Direct shear test**: define cohesion C and effective internal friction angle φ';
- **Proctor test**: define compacted soil dry density or maximum dry density γ_d;
- **Sand dry unit weight**: define uncompacted soil dry density $\gamma_{d,uncompacted}$;
- **Specific gravity**: define density of grain solid;
- **Oedometer**: define elastic modulus E of sand;

International Journal of Engineering Research & Technology (IJERT)
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Vol. 9 Issue 09, September-2020

Figure III.2: Weak sand

Figure III.3: River sand

Figure III.4: Stream sand

Table III.1: Results from testing of three type of sand

Sand types	Experiment's type						
	Sieve analysis	Direct shear test		Proctor test	Sand dry unit weight	Specific gravity	Oedometer
		C (kPa)	φ' (*Degrees*)	γ_d (*kN/m³*)	$\gamma_{d,uc}$ (*kN/m³*)	G_s	*E (kPa)*
Weak sand	Poorly graded sand (**SP**)	0	35	17.4	13.45	2.642	48000
River sand	Poorly graded sand (**SP**)	0	38	18.4	13.73	2.596	51000
Stream sand	Well graded sand (**SW**)	0	41	19.5	14.61	2.582	70000

III.2 Calculation

III.2.1 Site survey

1. Borey 1
   - **Location**: Posenchey District, Phnom Penh.
   - **Useful information summary as following**:
     - Backfilled soil type = made ground clean sand;
     - Backfilled soil depth = 1.8 *m*;
     - Foundation type = deep foundation;
     - Driven pile (0.3x0.3x7 *m*) x 2;
     - Type of building = flat;
     - Number of floors = 2 floors (ground floor included);
2. Borey 2
   - **Location**: Chroy Changva District, Phnom Penh.
   - **Useful information summary as following**:
     - Backfilled soil type = made ground sand;
     - Backfilled soil depth = 5.5 *m*;
     - Foundation type = deep foundation;
     - Driven pile (0.3x0.3x34 *m*) x 4;
     - Type of building = flat;
     - Number of floors = 3 floors (ground floor included);
3. Borey 3
   - **Location**: Meanchey District, Phnom Penh.
   - **Summary useful information data as following**:
     - Backfilled soil type = made ground sand;
     - Backfilled soil depth = 5.5 *m*;
     - Foundation type = deep foundation;
     - Driven pile (0.3x0.3x31 *m*) x2;
     - Type of building = flat;
     - Number of floors = 4 floors (ground floor included);

Borey: groups of houses having the same size and form, especially family houses that have no more than 4 floors.
1: assumed order number.

III.2.2 Analysis

For the analysis, natural soil consolidation affected by backfilled soil and shallow foundation is assumed to be completed, pinned support condition of foundation is used.

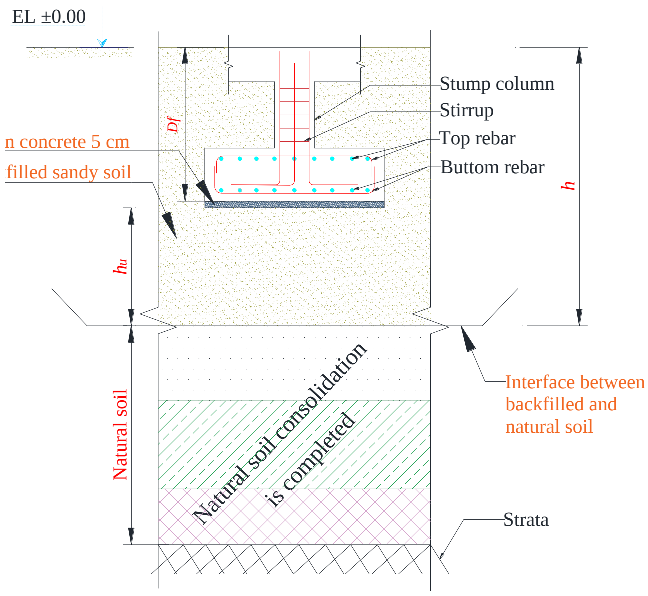

Figure III.5: General section plan for shallow foundation

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 09, September-2020

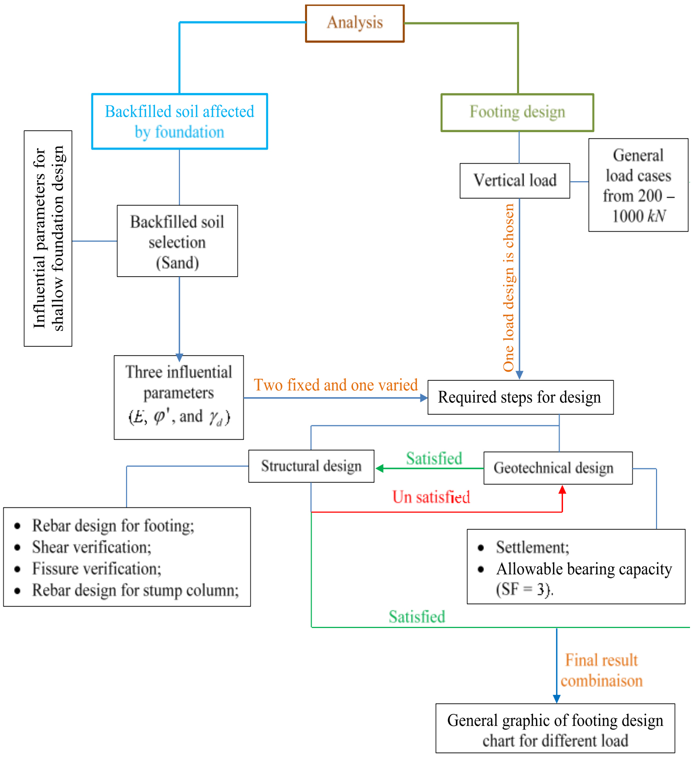

Figure III.6: Detail schema for analysis

Note 1:
Procedure to use general graphics is indicated as following:

- Choose *E* of soil on axe X;
- Vertical translation to value of φ' then γ_d;
- Horizontal translation to vertical axe of allowable load of bearing capacity in (*kN*);
- From the same *E* to footing's size curve by vertical translation then horizontal translation to footing's size at the right hand side. (See example in figure **III.7**).

Note 2:
Procedure to use graphic of minimum backfilled soil depth is indicated as following:

- Have to know first *B* width of footing from general graphics of footing design chart above;
- Choose *E* of soil on axe-X;
- Vertical translation to value of load design curve (**SLS**);
- Horizontal translation to vertical axe of *B*/*hu* (even load design or odd load design);
- Replace the value *B* then obtain *hu*;
- $h_u + Df = h$. (see figure **III.5**)

Note 3:
According to the graphics above, the interval and minimum values of parameters that are considered in using shallow foundation must be verified as following:

- First step: soil properties for allowable load verification
  - E = 8000 - 80000 *kPa*;
  - φ' = 27 - 43 *degrees;*
  - γ_d = 16 - 21 *kN/m³;*
  - $Q_{allow} \geq Q_{LD}$ (design load)
- Second step: minimum backfilled soil depth (after first step is verified and *B* is deduted from general graphics of footing design chart)
  - Minimum backfilled soil depth (h) = $h_u + Df$

International Journal of Engineering Research & Technology (IJERT)
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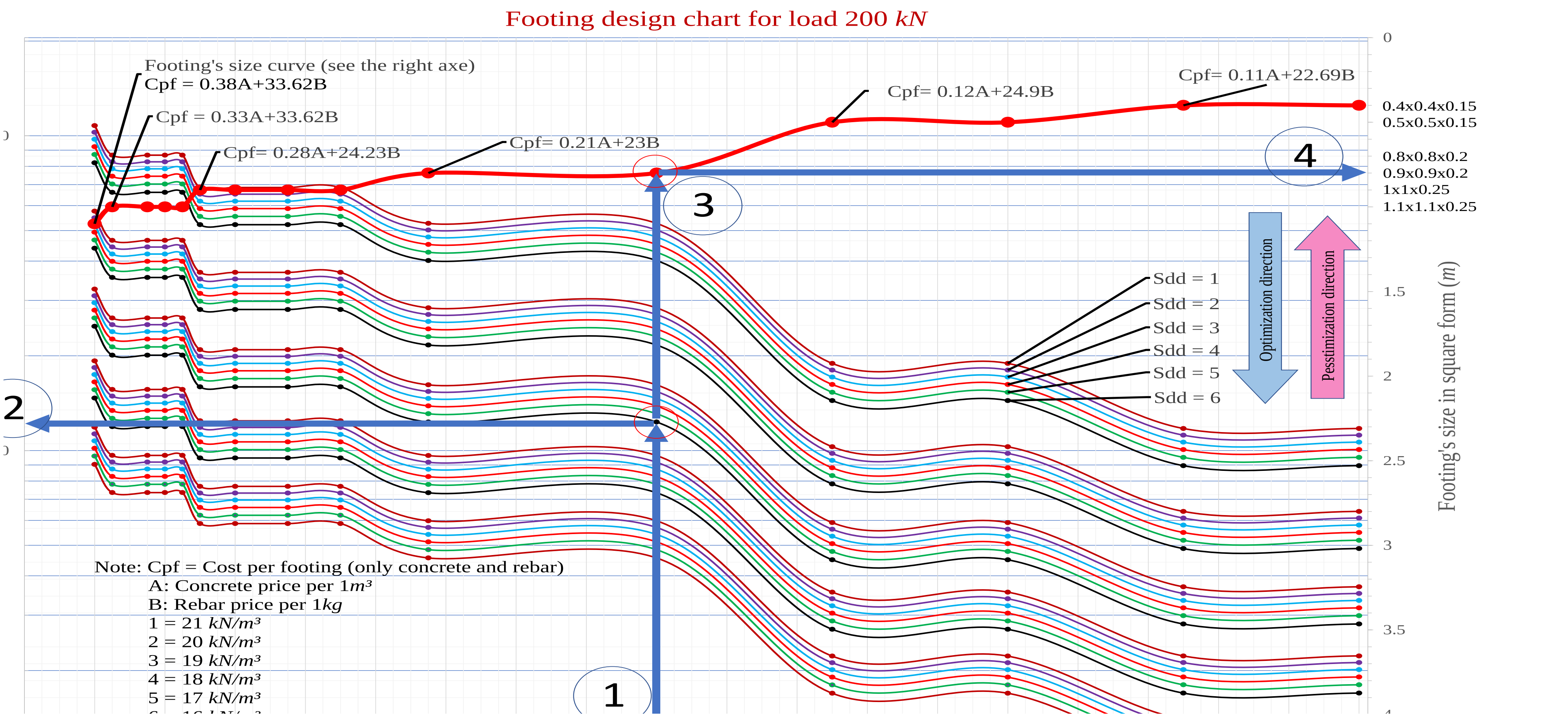

Figure III.7: Example of utilization of footing design chart for load 200 kN (do the same for other charts)

International Journal of Engineering Research & Technology (IJERT)
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Vol. 9 Issue 09, September-2020

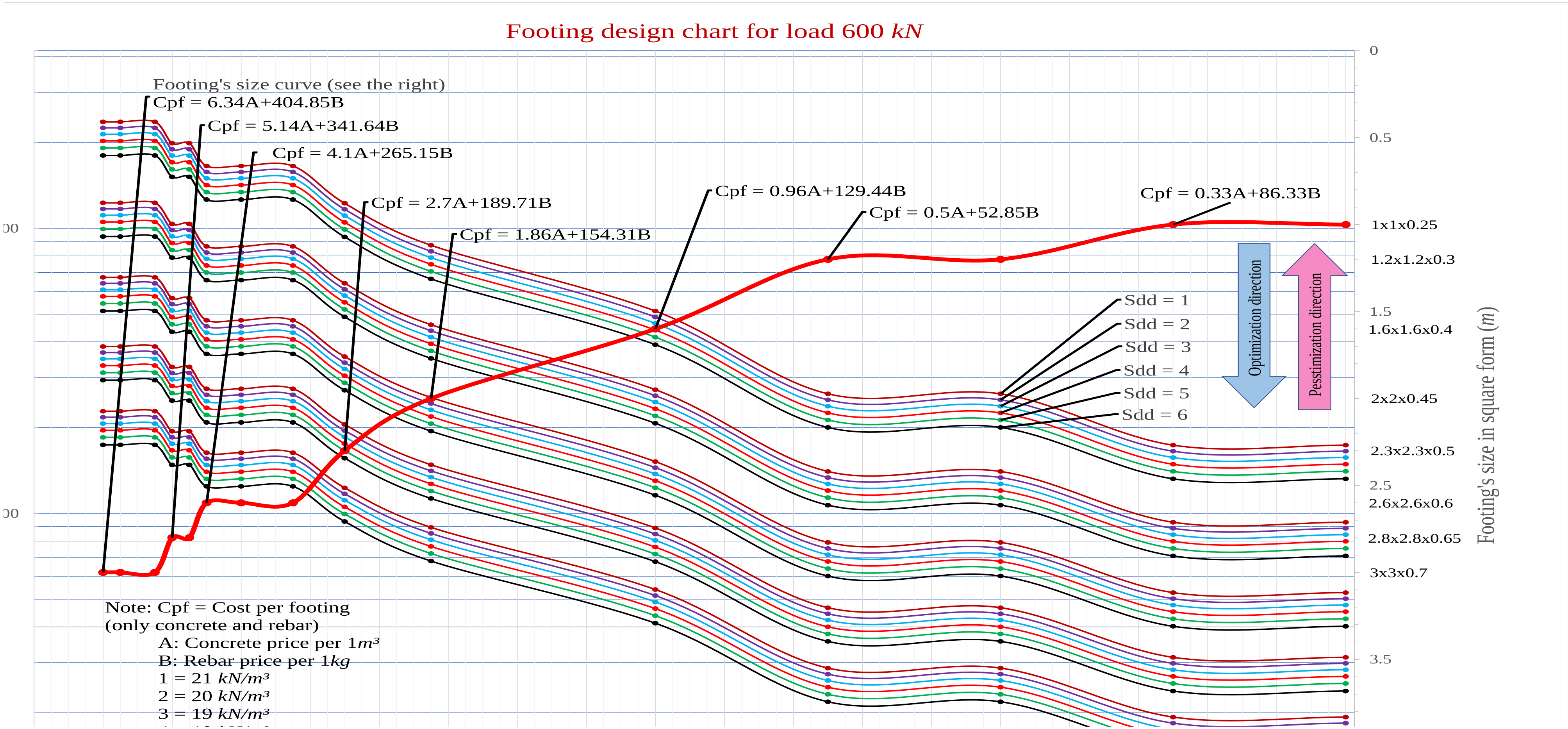

Figure III.8: Footing design chart for load 600 *kN*

International Journal of Engineering Research & Technology (IJERT)
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Vol. 9 Issue 09, September-2020

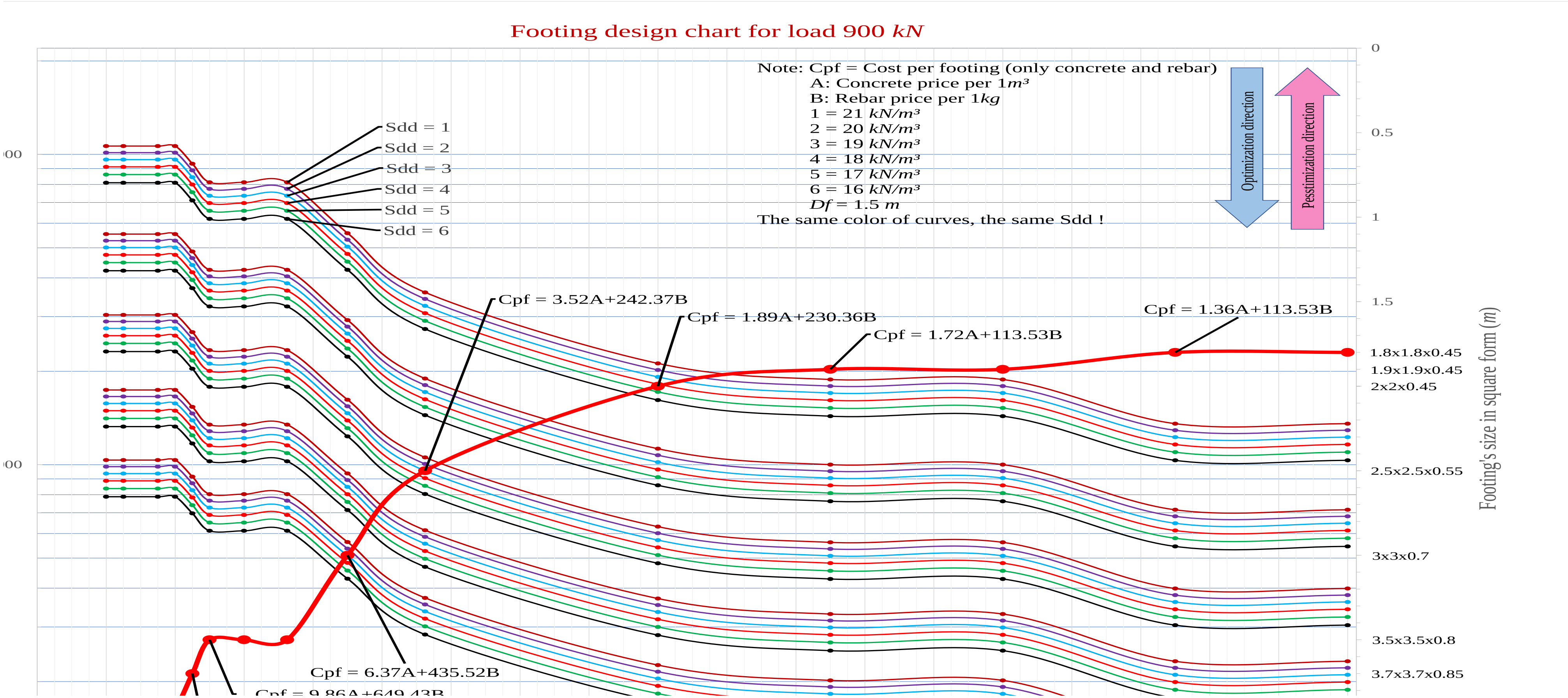

Figure III.9: Footing design chart for load 900 kN

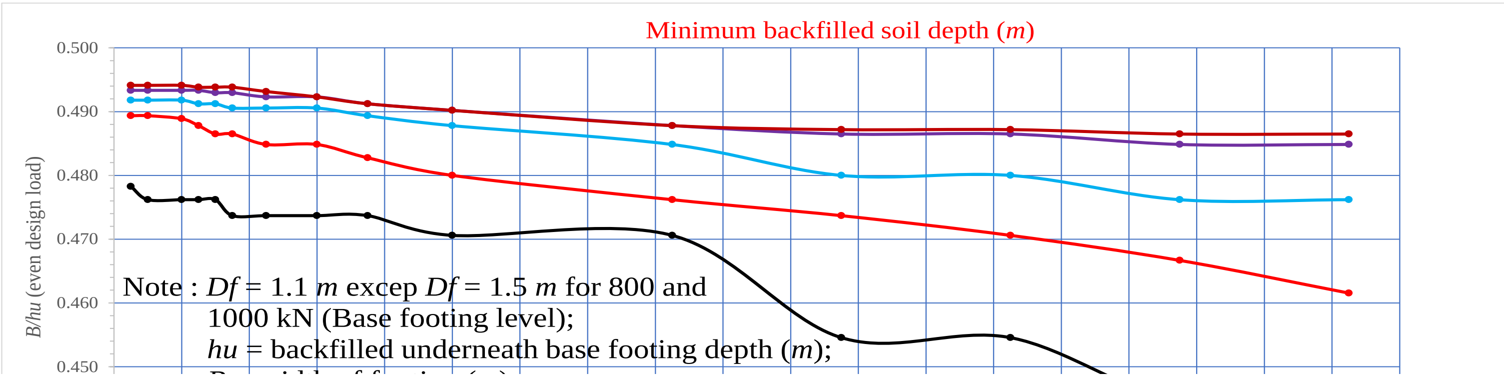

Figure III.10: Minimum backfilled soil depth for even load

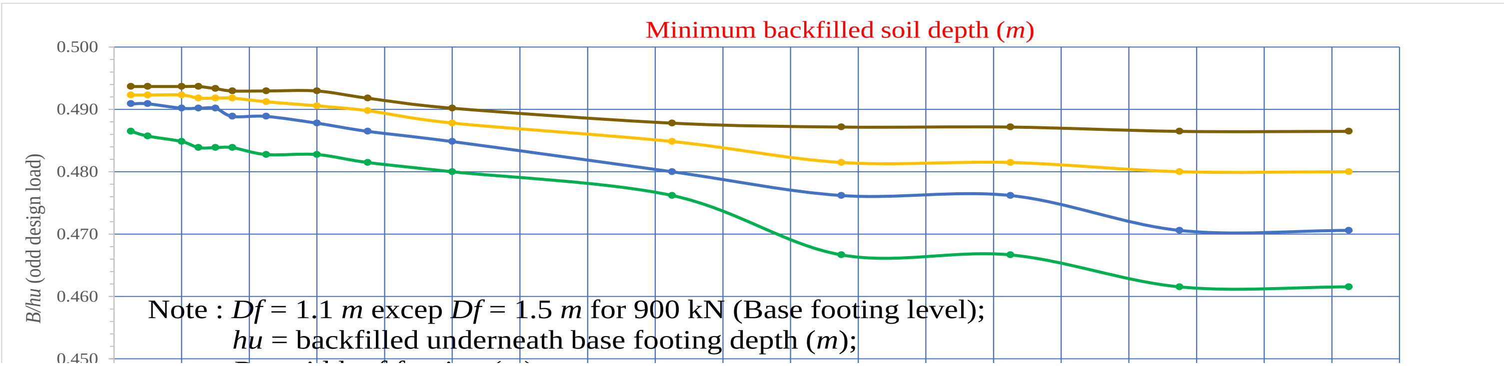

Figure III.11: Minimum backfilled soil depth for odd load

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 09, September-2020

Table III.2: Footing design and backfilled soil depth for different loads design of three recommendation of sandy soil

Load design (kN)	Weak sand (**SP**)				River sand (**SP**)				Stream sand (**SW**)			
	Footing's size (m)	Rebar (top, bottom, and both direction	Underneath base footing depth h_u (m)	Backfilled soil depth h (m)	Footing's size (m)	Rebar (top, bottom, and both direction	Underneath base footing depth h_u (m)	Backfilled soil depth h (m)	Footing's size (m)	Rebar (top, bottom, and both direction	Underneath base footing h_u depth (m)	Backfilled soil depth h (m)
200	0.8x0.8x0.2	4DB12@200	1.7	2.8	0.7x0.7x0.2	4DB12@160	1.5	2.6	0.5x0.5x0.15	4DB14@100	1.1	2.2
300	0.9x0.9x0.25	5DB12@160	1.9	3	0.7x0.7x0.2	4DB12@160	1.5	2.6	0.7x0.7x0.2	4DB12@160	1.5	2.6
400	1x1x0.25	5DB12@160	2.1	3.2	1x1x0.25	5DB12@160	2.1	3.2	0.8x0.8x0.2	4DB12@200	1.7	2.8
500	1.2x1.2x0.3	6DB12@180	2.5	3.6	1.1x1.1x0.25	8DB12@110	2.3	3.4	0.8x0.8x0.2	7DB20@70	1.7	2.8
600	1.2x1.2x0.3	6DB12@180	2.5	3.6	1.2x1.2x0.3	6DB12@180	2.5	3.6	1x1x0.25	6DB20@120	2.1	3.2
700	1.3x1.3x0.3	10DB16@100	2.7	3.8	1.3x1.3x0.3	10DB16@100	2.7	3.8	1.2x1.2x0.3	9DB14@100	2.5	3.6
800	1.8x1.8x0.45	10DB14@150	3.7	5.2	1.8x1.8x0.45	10DB14@150	3.7	5.2	1.6x1.6x0.4	9DB12@150	3.3	4.8
900	1.9x1.9x0.45	10DB14@150	3.9	5.4	1.9x1.9x0.45	10DB14@150	3.9	5.4	1.8x1.8x0.45	10DB14@150	3.7	5.2
1000	1.9x1.9x0.45	10DB14@150	3.9	5.4	1.9x1.9x0.45	10DB14@150	3.9	5.4	1.8x1.8x0.45	10DB14@150	3.7	5.2
Note: Stump column's size is 0.3x0.3 m, 4DB16 and RB8@200 for all loads design.												

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 9 Issue 09, September-2020

III.2.3 Application

In this part, all survey data from many Boreys are applied if the backfilled sany soil at sites have sufficient capacity can allow shallow foundaton stands on it or not and then cost-effective study (see figure **III. 12**).

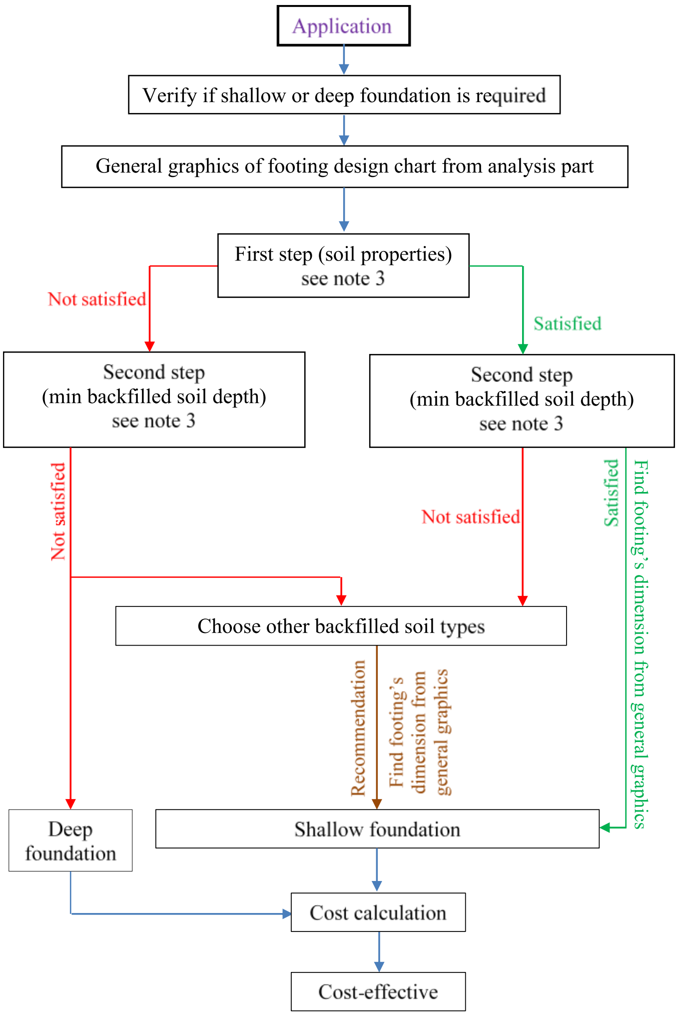

Figure III.12: Flow chart for cost-effective

III.2.3.1 Verification

1. Borey 1
   - Verification:
     - First step: satisfied;
     - Second step: not satisfied;
   - Conclusion: deep foundation is required due to not enough backfilled soil depth;
   - Change to shallow foundation: choose other backfilled soil types.

2. Borey 2
   - Verification:
     - First step: not satisfied;
     - Second step: not satisfied;
   - Conclusion: deep foundation is required due to not enough backfilled soil depth;
   - Change to shallow foundation: choose other backfilled soil types.

3. Borey 3
   - Verification:
     - First step: not satisfied;
     - Second step: not satisfied;
   - Conclusion: deep foundation is required due to not enough backfilled soil depth;
   - Change to shallow foundation: choose other backfilled soil types.

III.2.3.2 Recommendation

Three often utilized types of sand in country:

- Weak sand: Poorly graded sand (**SP**), (see figure **III.2**);
- River sand: Poorly graded sand (**SP**), (see figure **III.3**);
- Stream sand: Well graded sand (**SW**); (see figure **III.4**).

Table III.3: Cost of deep foundation at site versus shallow foundation with three recommended sandy soil for backfilling

Name	Deep foundation	Shallow foundation		
		Weak sand	River sand	Stream sand
Borey 1	$ 522	Can't use because of not enough backfilled soil depth!		
Borey 2	$ 2684	$ 304	$ 316	$ 335
Borey 3	$ 1471	$ 607	$ 638	$ 721

III.2.3.3 Cost-effective

Table III.4: Cost optimization per foundation of each application

Name	Foundation's type	Optimal cost	Sand type
Borey 1	Deep foundation	$ 522	
Borey 2	Shallow foundation	$ 304	Weak sand
Borey 3	Shallow foundation	$ 607	

III. CONCLUSION AND FUTURE WORK

IV.1 Conclusion

According to the point of analysis, experiment, and application, the final results will be concluded as following

- Analysis: general minimum and maximum underneath base footing depth h_u (see figure **III.5**) that can support shallow foundation for three types of sandy soil:

Table IV.1: Minimum backfilled soil depth for each sand

Sand type	$\gamma_{un\ compacted}$ (kN/m^3)	$\gamma_{compacted}$ (kN/m^3)	h_u (m) Thickness of compacted soil at the base of footing	Dimension of footing (m)
Weak sand (**SP**)	13.43	17.41	1.7-3.9	0.8x0.8x0.2-1.9x1.9x0.45

River sand (**SP**)	13.73	18.4	1.5-3.9	0.7x0.7x0.2-1.9x1.9x0.45
Stream sand (**SW**)	14.61	19.55	1.1-3.7	0.5x0.5x0.15 - 1.9x1.9x0.45

- Optimal backfilled soil type: Weak sand (**SP**);
- Application: general limited values are assumed for load 600 and 900 *kN* that shallow foundation is more effective than deep foundation as following:

Table IV.2: General limited values are assumed that shallow foundation is more effective than deep foundation as following:

Design load (*kN*)	600	900
Volume of concrete (footing and stump column) *m³*	0.5	0.75
Mass of rebar (footing and stump column) *kg*	53	90
Backfilled soil depth (*m*)	3.6	5.4
Pile depth (0.3x0.3 *m*) (*m*)	-	14.4
Optimal type of sand	Weak sand (**SP**)	

IV.2 Future work

For the future work, many factors will be continued to consider in this thesis for more effective shallow foundation as following:

- Natural soil consolidation;
- Standard compaction method at in situ;

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