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ALLOWABLE PRESSURE FOR RIGID STRIP FOUNDATIONS

BY

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Abstract. The design of foundations is done considering both the strength and the settlement of the soil, under expected loading conditions and soil conditions. In the case of ordinary buildings founded on favourable ground the design can be done using prescriptive design procedures – comparing the actual pressures with the allowable pressures. The values for the allowable pressure (conventional pressure), provided in the Romanian technical regulations, are established empirically. New values for the allowable pressure for rigid strip foundations were proposed. The study showed that the values of the allowable pressure corresponding to a settlement of 6 cm are lower than the values of the conventional pressures, plastic pressures and the ultimate pressure obtained using the specifications from the Romanian technical regulations.

Keywords: limit state; foundation; bearing capacity; allowable settlement; finite element method.

1. Introduction

In the case of ordinary buildings founded on favourable ground the design can be done using prescriptive design procedures – comparing the actual pressures with the allowable pressures (conventional pressures). The allowable pressure can be established by dividing the ultimate bearing capacity by a factor

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of safety (typically 3.0) or by determining the bearing pressure which corresponds to an acceptable level of settlement. For example, for multi-story building with structural walls made from panels or bricks masonry, without reinforcement, the medium settlement, s_m, has the acceptable level of 10 cm (Annex H from NP 112-2014).

The aim of the SLS check is to prove that any displacement or deformation of the foundation, as effect of the ground deformation, does not exceed limiting values of structural deformation and foundation movement. The methods based on the theory of elasticity should be used only if the stresses in the ground are such that no significant yielding occurs and if the stress-strain behaviour of the ground may be considered to be linear. So, another SLS design criteria involves limiting the design pressures applied through the footing to the ground at the value of the initial critical pressure. In this context, the allowable pressure is the initial critical pressure which is the limiting pressure corresponding to a certain development of the plastic point (Bejan, 2013a; Stanciu, 1994). In the Russian (SNIP 2.02.01.-83) and the Romanian (NP 112:2014) technical regulations the development of the plastic points (points where the shear stress equals the shear strength) is limited to a depth equal to a quarter from the foundation width ($z_{max} = B/4$):

$$p_{pl} = m_l p_{cr.in.} = m_l \left(\gamma B N_1 + q N_2 + c N_3\right), \tag{1}$$

where m_l is the coefficient of working conditions (Table H.7, NP 112:2014); γ – the soil weight density, q – the overload at the footing level and laterally displayed from it ($q = \gamma\ D_f$), D_f is the foundation depth, c is cohesion of the soil and N_1, N_2, N_3 are coefficients that depend on the angle of shearing resistance (ϕ).

$$N_1 = \frac{0.25\pi}{\cot\phi - \pi/2 + \phi};\ N_2 = 1 + \frac{\pi}{\cot\phi - \pi/2 + \phi};\ N_3 = \frac{\pi\cot\phi}{\cot\phi - \pi/2 + \phi}. \tag{2}$$

Multiplying the initial critical pressure with a coefficient greater than one (m_l = 1.1 – 2.0) leads to a greater development of the plastic points and so to violation of the linear deformable hypothesis.

Another problem that appear here is that the initial critical pressure is established for a half space acted by a uniform distributed pressure. In reality, the soil pressure distribution under the footing is not uniform. In this conditions, the values of the limit pressure which determines the development of the plastic points to a depth equal with $B/4$ are smaller because the stresses concentrate at the footing edges and the stresses are redistributed from the plasticized zone to the elastic zones (Bejan, 2013a; Bejan, 2013b).

The source of the conventional pressure values provided in the Romanian technical regulations is not known. Thus, in this work, through back analysis, were proposed new values for the allowable pressure for rigid strip foundations. For this, in the first stage were established the pressure-settlement curves for rigid strip foundations founded on different types of soils using the guidance values of geotechnical parameters recommended in NP 122:2010 (Table 1). The values of the pressures corresponding to certain values of settlements (2, 4, 6 and 8) – the allowable pressure, obtained from the pressure-settlement curves, are compared with the conventional pressures, plastic pressures and the ultimate pressure obtained using the specifications from the Romanian technical regulations.

2. Definition of the problem

The allowable pressure represents the value of the pressure that causes certain settlements compatible with the structural system without losing the stability of the ground-foundation-structure system. In this paper, it is evaluated the allowable pressure for rigid strip foundations acted by vertical loads using the finite element method (FEM) implemented in the Plaxis2D software. For this purpose, the numerical formulation of the Mohr-Coulomb linear elastic-perfectly plastic model (MC) was used with a triangular mesh of 15 nodes elements (Fig. 1).

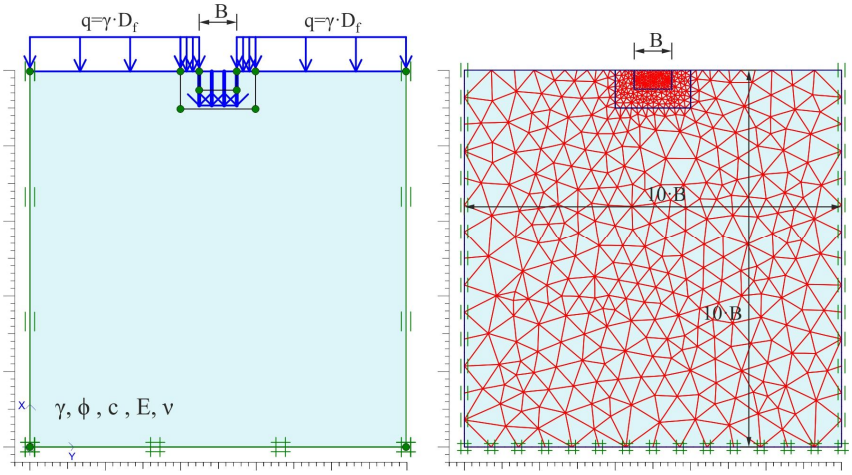


Fig. 1 – The model used for the evaluation of the allowable pressure.

The vertical force acting on the rigid strip foundation, with 1.0 m width, was taken in account, in the model, by imposing a uniform settlement (s). The effect of soil above the footing level is considered through the overload $q = \gamma \cdot D_f$ (Fig. 1).

Table 1

The Guidance Values of the Geotechnical Parameters Used for the Determination of the Allowable Pressures for Rigid Strip Foundations

Void ratio, e	Geotechnical characteristics	Units	Cohensionless soils				Cohesive soils with $S \geq 0.8$							
							$I_P < 10\%$		$10\% < I_P < 20\%$			$I_P > 20\%$		
							I_C							
			Sands with gravel and coarse sands	Medium sands	Fine sands	Silty sands	0.75 – 1.00	0.25 – 0.75	0.75 – 1.00	0.50 – 0.75	0.25 – 0.50	0.75 – 1.00	0.50 – 0.75	0.25 – 0.50
0.45	ϕ	°	36	33	31	30	25	23	22	20				
	c	kPa	0	0	0	0	10	8	30	25				
	γ	kN/m^3	18	18	18	18	20	20	20.5	20.5				
	E	MPa	40		35	30	32	30	34	32				
0.55	ϕ	°	33	31	30	28	24	22	21	19		17		
	c	kPa	0	0	0	0	7	6	24	22		53		
	γ	kN/m^3	17	17	17	17	19.5	19.5	20	20		20.5		
	E	MPa	40		35	30	24	22	27	25		28		
0.65	ϕ	°	33	31	27	24	22	20	20	18	16	16	15	12
	c	kPa	0	0	0	0	5	4	20	18	16	44	37	29
	γ	kN/m^3	16	16	16	16	19	19	19.5	19.5	19.5	20	20	20
	E	MPa	30		25	18	16	14	22	19	17	24	21	18
0.75	ϕ	°			23	22		17	19	17	15	15	14	11
	c	kPa			0	0		2	16	15	13	35	33	27
	γ	kN/m^3			15	15		18.5	19	19	19	19.5	19.5	19.5
	E	MPa			18	11		10	17	14	11	21	18	15
0.85	ϕ	°							18	16	13	15	13	10
	c	kPa							18	15	13	31	28	23
	γ	kN/m^3							18.5	18.5	18.5	19	19	19
	E	MPa							14	11	8	18	15	12
0.95	ϕ	°							16	14	11	13	11	8
	c	kPa							12	10	9	27	24	21
	γ	kN/m^3							18	18	18	18.5	18.5	18.5
	E	MPa							11	8	5	15	12	9
1.05	ϕ	°									10	11	9	5
	c	kPa									7	24	21	19
	γ	kN/m^3									18	18	18	18
	E	MPa									3	12	9	7
v		–	0.3				0.35				0.4			

The values of the geotechnical parameters (γ – weight density, ϕ – angle of shear resistance, c – cohesion, E – elastic modulus and ν – Poisson's coefficient), used for modelling the foundation soil, are centralized in Table 1. These values have been taken from Annex A6 of NP 122:2010.

The conventional pressures, p_{conv}, are determined by interpolating values from tables D1 to D5 from Annex D, NP 112:2014.

The initial critical pressures (plastic pressures) are determined using the relationship from Annex H.5 from NP 112:2014 for foundations with the width (B) of 1.00 m and the foundation depth (D_f) of 2.00 m. The values of the weight density, cohesion and internal friction angle are equal with the characteristic values from Table 1, because in the case of SLS the partial safety coefficients are equal with 1.

The ultimate pressures are determined using the relationship from Annex F from NP 112:2014 for foundations with width B = 1.00 m and foundation depth D_f = 2.00 m.

$$p_{ul} = \gamma B N_\gamma + q N_q + c N_c, \tag{3}$$

where γ is the soil weight density, q – the overload at the footing level and laterally displayed from it ($q = \gamma D_f$), D_f is the foundation depth, c – cohesion of the soil and N_γ, N_q, N_c are coefficients that depend on the angle of shearing resistance (ϕ).

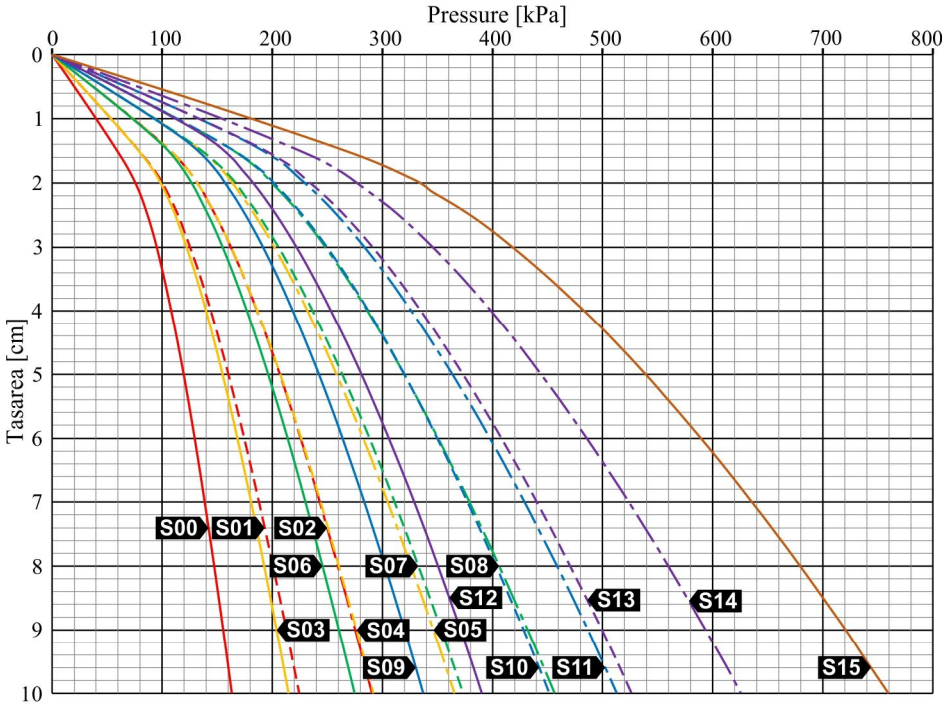
$$N_q = \tan^2\left(45 + \frac{\phi}{2}\right) e^{\pi \tan\phi};\ N_c = (N_1 - 1)\cot\phi;\ N_\gamma = 2(N_q - 1)\tan\phi. \tag{4}$$

The evaluation of the ultimate critical pressure is done taking into account the partial factors corresponding to the Design Approaches (Annex B from NP 112:2014). Thereby, for the Design Approach 1, Combination 1 (DA1C1) the value of weight density is obtained by multiplying the characteristic values from Table 1 with a partial factor of 1.35 and the design values of the cohesion and angle of shear resistance by multiplying the characteristic values from Table 1 with a coefficient of 1.00. For the Design Approach 1, Combination 2 (DA1C2) the design value of the weight density is identic with the characteristic value from Table 1, the design value of the cohesion is obtained by multiplying the characteristic values from Table 1 with the partial factor of 1.40 and the design values of the angle of shear resistance are obtained by multiplying the characteristic values with a partial factor of 1.25 (applied to the tangent).

3. Results

3.1. The Allowable Pressures for Cohesive Soils with I_P > 20%

The pressure-settlement curves, for cohesive soils with I_P > 20%, are obtained using the Plaxis2D software (Fig. 2). In this case, the values of the pressures corresponding to settlements of 2, 4, 6 and 8 cm and the values of the conventional pressure, initial critical pressure and ultimate pressure are presented in Table 2.



Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S00	5	19	18.0	7000	0.4
S01	9	21	18.0	9000	0.4
S02	11	24	18.0	12000	0.4
S03	8	21	18.5	9000	0.4
S04	11	24	18.5	12000	0.4
S05	13	27	18.5	15000	0.4
S06	10	23	19.0	9000	0.4
S07	13	28	19.0	12000	0.4
S08	15	31	19.0	15000	0.4

Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S09	11	27	19.5	1500	0.4
S10	14	33	19.5	18000	0.4
S11	15	35	19.5	21000	0.4
S12	12	29	20.0	18000	0.4
S13	15	37	20.0	21000	0.4
S14	16	44	20.0	24000	0.4
S15	17	53	20.5	28000	0.4

Fig. 2 − Load-settlement curves for cohesive soils with I_P > 20%.

In the first stage the soil behaviour is linear elastic until a limit pressure which corresponds to appearance of the plastic points in the ground. In the second stage the soil has an elastic-plastic behaviour and the settlement rate is higher than the one from the first stage.

Table 2

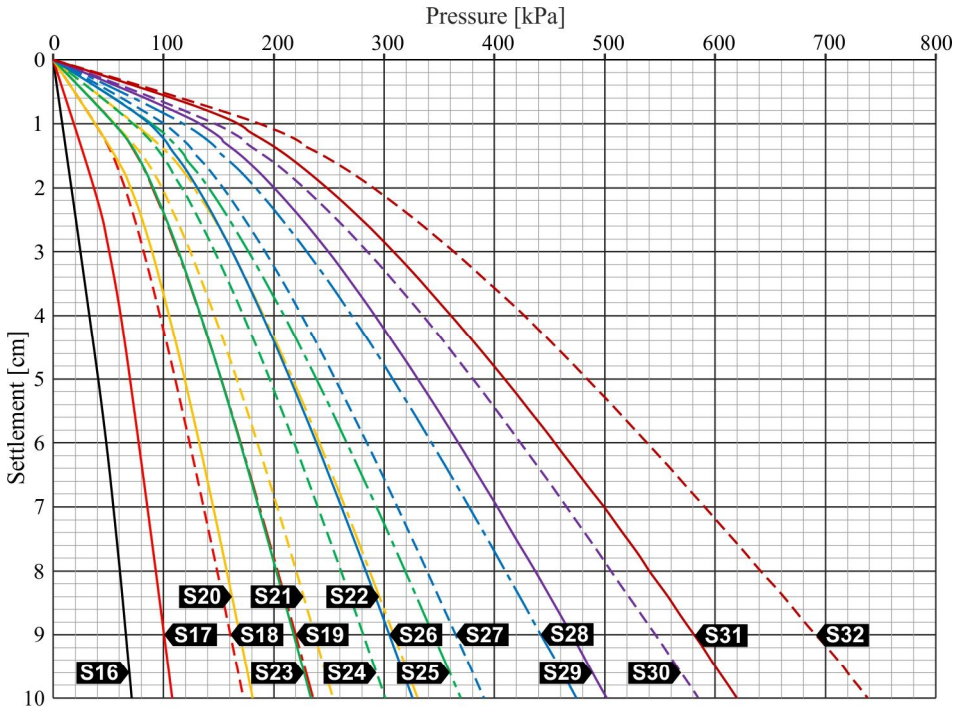
The Values of the Allowable, Initial Critical, Conventional and Ultimate Pressures for Cohesive Soils With $I_P > 20\%$

Sample	p_{all}				$p_{cr.in.}$	$m_l p_{cr.in.}$	$p_{conv.}$	$p_{ul.}$		
	2 cm	4 cm	6 cm	8 cm				No App.	DA1C1	DA1C2
S00	75	108	**130**	147	117	129	185	181	**134**	146
S01	100	144	**174**	200	147	206	225	251	**186**	193
S02	130	186	**226**	259	173	242	265	315	**234**	234
S03	98	140	**168**	192	143	157	225	237	**176**	184
S04	132	187	**226**	259	175	245	260	318	**236**	237
S05	163	232	**282**	325	204	286	295	395	293	**286**
S06	127	176	**214**	245	165	182	265	291	216	**220**
S07	167	237	**288**	332	210	294	295	409	303	**295**
S08	198	187	**350**	405	243	340	320	505	374	**354**
S09	157	219	**263**	302	191	210	320	350	**259**	260
S10	202	288	**350**	403	245	343	350	495	367	**351**
S11	227	327	**396**	458	265	371	380	553	410	**387**
S12	183	253	**306**	350	210	231	395	397	294	**291**
S13	234	333	**407**	469	277	388	430	580	438	**405**
S14	275	397	**485**	559	324	356	460	704	521	**484**
S15	334	482	**588**	678	386	540	565	873	647	**589**

All values of the allowable pressure corresponding to a settlement of 6 cm are higher than the minimum values of the ultimate pressure. The values of the initial critical pressures are lower than the values of the allowable pressure corresponding to a settlement of 6 cm but higher than those corresponding to a settlement of 2 cm.

3.2. The Allowable Pressures for Cohesive Soils with $10\% < I_p \leq 20\%$

The pressure-settlement curves, for cohesive soils with $10\% < I_p \leq 20\%$, are obtained using the Plaxis2D software (Fig. 3). In this case, the values of the pressures corresponding to settlements of 2, 4, 6 and 8 cm and the values of the conventional pressure, initial critical pressure and ultimate pressure are presented in Table 3.



Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S16	10	7	18.0	3000	0.35
S17	11	9	18.0	5000	0.35
S18	14	10	18.0	8000	0.35
S19	16	21	18.0	11000	0.35
S20	13	13	18.5	8000	0.35
S21	16	15	18.5	11000	0.35
S22	18	18	18.5	14000	0.35
S23	15	13	19.0	11000	0.35
S24	17	15	19.0	14000	0.35
S25	19	16	19.0	17000	0.35

Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S26	16	16	19.5	17000	0.35
S27	18	18	19.5	19000	0.35
S28	20	20	19.5	22000	0.35
S29	19	22	20.0	25000	0.35
S30	21	24	20.0	27000	0.35
S31	20	25	20.5	32000	0.35
S32	22	30	20.5	34000	0.35

Fig. 3 − Load-settlement curves for cohesive soils with 10% < $I_P \leq$ 20%.

In this case, the ratio between the values of the allowable pressure (corresponding to a settlement of 6 cm) to the values of the initial critical pressure takes values from 1.11 for S19 (ϕ = 16°; c = 21 kPa; E = 11,000 kPa) to 1.63 for S32 (ϕ = 22°; c = 30 kPa; E = 34,000 kPa). These ratios are similar with the values of the coefficient of working conditions (m_1) which takes the value of 1.1 for I_C < 0.50 and the value of 1.4 for I_C > 0.50. For soils with E < 8,000 (S16, S17 and S18) the ratio is lower than 1.0.

Table 3

The Values of the Allowable, Initial Critical, Conventional and Ultimate Critical Pressures for Cohesive Soils with 10% < $I_P \leq 20\%$

Sample	p_{all}				$p_{cr.in.}$	$m_l p_{cr.in.}$	$p_{conv.}$	$p_{ul.}$		
	2 cm	4 cm	6 cm	8 cm				No App.	DA1C1	DA1C2
S16	16	32	**48**	61	95	104	170	152	**113**	119
S17	37	61	**77**	93	108	119	200	183	**136**	140
S18	65	97	**123**	148	130	182	220	244	181	**178**
S19	90	134	**170**	203	154	215	245	313	232	**220**
S20	70	105	**132**	157	140	154	225	258	191	**190**
S21	98	146	**185**	220	171	239	245	353	261	**247**
S22	128	192	**241**	287	204	285	265	456	344	**308**
S23	91	134	**170**	203	156	172	265	307	227	**219**
S24	117	172	**219**	262	182	255	270	388	287	**267**
S25	142	209	**267**	319	206	288	280	475	352	**316**
S26	131	190	**239**	282	182	200	270	374	277	**261**
S27	155	226	**284**	339	210	294	290	468	347	**316**
S28	183	271	**341**	410	242	339	305	585	433	**381**
S29	202	292	**366**	436	245	343	305	571	423	**379**
S30	227	337	**423**	504	281	393	325	709	525	**453**
S31	247	359	**453**	539	277	388	320	674	499	**433**
S32	289	425	**539**	640	335	469	350	884	655	**549**

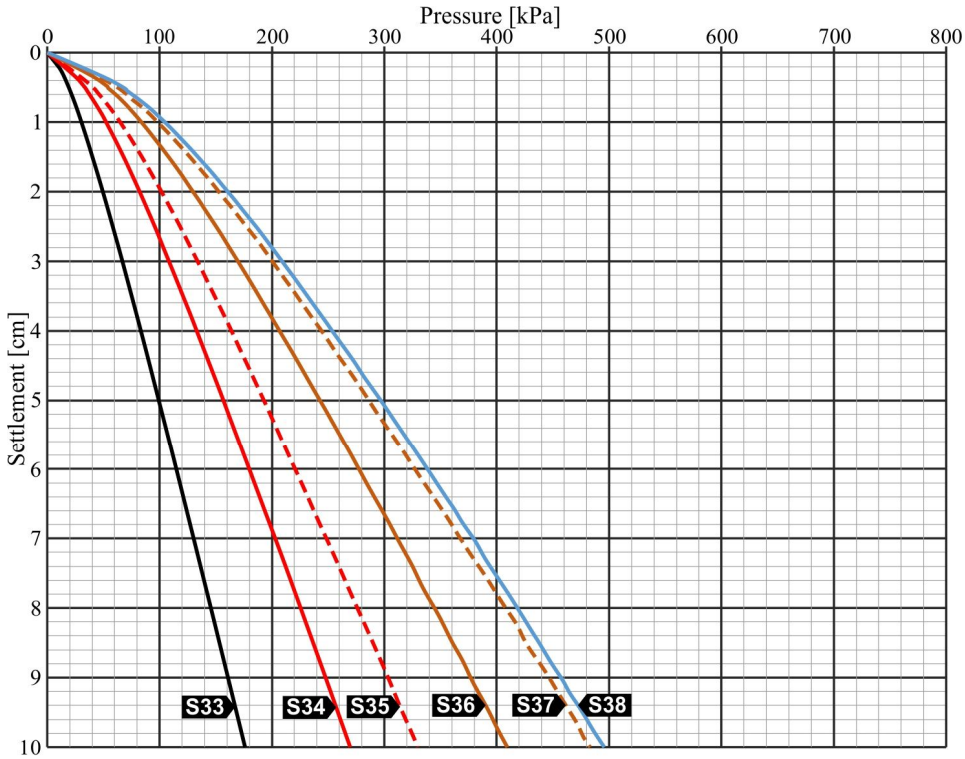
3.3. The Allowable Pressures for Cohesive Soils with $I_P \leq 10\%$

The pressure-settlement curves, for cohesive soils with $I_P \leq 10\%$, are obtained using the Plaxis2D software (Fig. 4). In this case, the values of the pressures corresponding to settlements of 2, 4, 6 and 8 cm and the values of the conventional pressure, initial critical pressure and ultimate pressure are presented in Table 4.

Table 4

The Values of the Allowable, Initial Critical, Conventional and Ultimate Critical Pressures for Cohesive Soils with $I_P \leq 10\%$

Sample	p_{all}				$p_{cr.in.}$	$m_l p_{cr.in.}$	$p_{conv.}$	p_{ul}		
	2 cm	4 cm	6 cm	8 cm				No App.	DA1C1	DA1C2
S33	50	84	116	145	113	124	270	223	165	157
S34	82	134	180	226	149	164	280	340	252	225
S35	102	164	221	275	172	241	305	434	321	276
S36	128	207	277	343	182	200	290	460	341	292
S37	152	243	327	407	210	294	325	584	433	357
S38	160	254	339	419	209	230	305	556	412	346



Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S33	17	2	18.5	10000	0.35
S34	20	4	19.0	14000	0.35
S35	22	5	19.0	16000	0.35

Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S36	22	6	19.5	22000	0.35
S37	24	7	19.5	24000	0.35
S38	23	8	20.0	26000	0.35

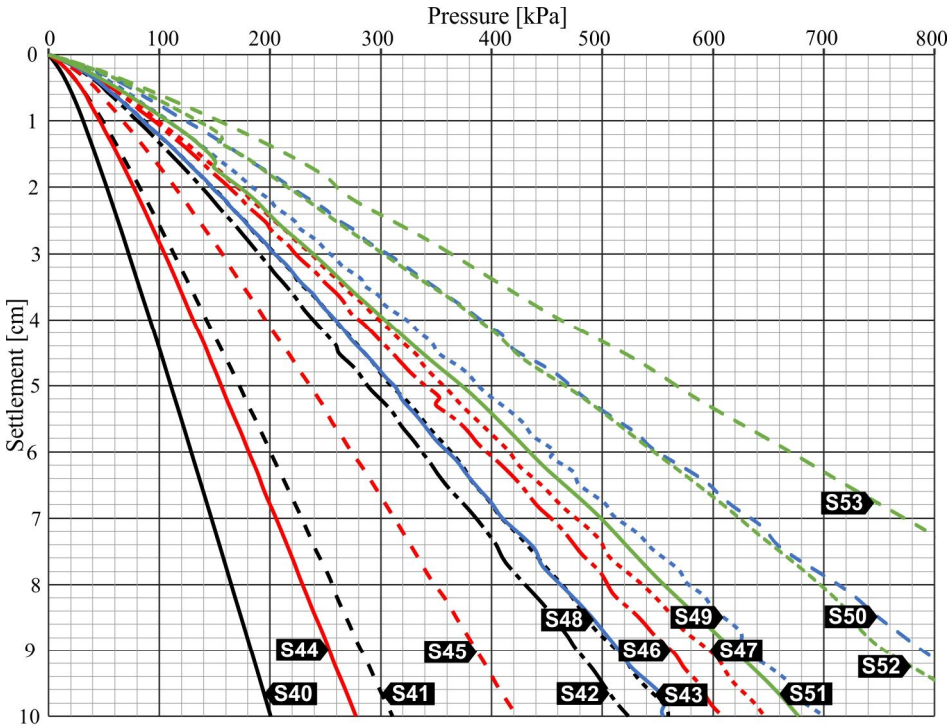
Fig. 4 – Load-settlement curves for cohesive soils with $I_P \leq 10\%$.

In this case, the ratio between the values of the allowable pressure (corresponding to a settlement of 6 cm) to the values of the initial critical pressure takes values from 1.03 for S33 (ϕ =17°; c=2kPa; E=10000 kPa) to 1.62 for S38 (ϕ = 23°; c = 8 kPa; E = 26,000 kPa). These ratios are similar with the values of the coefficient of working conditions (m_l) which takes the value of 1.1 for I_C = 0.25 – 0.50 and the value of 1.6 for I_C = 0.50 – 1.00.

3.4. The Allowable Pressures For Cohesionless Soils

The pressure-settlement curves, for cohesionless soils, are obtained using the Plaxis2D software (Fig. 5). In this case, the values of the pressures corresponding to settlements of 2, 4, 6 and 8 cm and the values of the

conventional pressure, initial critical pressure and ultimate pressure are presented in Table 5.



Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S40	22	0	15.0	11000	0.30
S41	24	0	16.0	18000	0.30
S42	28	0	17.0	30000	0.30
S43	30	0	18.0	30000	0.30
S44	23	0	15.0	18000	0.30
S45	27	0	16.0	25000	0.30
S46	30	0	17.0	35000	0.30
S47	31	0	18.0	35000	0.30

Sample	ϕ[°]	c[kPa]	γ[kN/m^3]	E [kPa]	ν
S48	31	0	16.0	30000	0.30
S49	31	0	17.0	40000	0.30
S50	33	0	18.0	40000	0.30
S51	33	0	16.0	30000	0.30
S52	33	0	17.0	40000	0.30
S53	36	0	18.0	40000	0.30

Fig. 5 − Load-settlement curves for cohesionless soils.

In this case, the ratio between the values of the allowable pressure (corresponding to a settlement of 6 cm) to the values of the initial critical pressure takes values from 1.15 for S40 (ϕ = 22°; c = 0 kPa; E = 110,000 kPa) to 2.04 for S53 (ϕ =36°; c = 0 kPa; E = 40,000 kPa). These ratios are similar with the values of the coefficient of working conditions (m_l) which takes the value of 1.3 for silty sands and the value of 2.0 for sands.

Table 5
The Values of the Allowable, Initial Critical, Conventional and Ultimate Pressures for Cohesionless Soils

Sample	p_{all}				$p_{cr.in.}$	$m_l\, p_{cr.in.}$	$p_{conv.}$	$p_{ul.}$		
	2 cm	4 cm	6 cm	8 cm				No App.	DA1C1	DA1C2
S40	52	92	129	165	112	168-202	150-300	276	204	177
S41	82	142	201	256	135	203-244	150-300	369	256	226
S42	138	238	337	429	184	277-332	200-350	624	408	351
S43	148	260	365	463	222	333-399	200-350	843	521	454
S44	77	131	180	229	119	215-227	250-350	309	229	194
S45	114	195	273	348	163	293-310	250-350	522	362	300
S46	160	277	395	503	209	377-398	350-500	796	521	429
S47	170	298	415	534	237	426-449	350-500	955	590	503
S48	147	259	360	461	210	420	500	849	590	447
S49	184	323	456	576	223	447	600	902	589	475
S50	217	392	549	712	269	539	600	1,233	761	619
S51	173	303	433	553	240	479	600	1,096	761	551
S52	218	391	548	698	254	509	700	1,164	761	585
S53	258	548	670	873	329	658	700	1,840	1,136	861

The values of the allowable pressures corresponding to the settlement of 6 cm, for different types of soils are presented in the Table 6. In the Table 7 are presented the values of the coefficient proposed to obtain the values of the allowable pressure for other values of the limiting settlement (s_{all}).

Table 6
Guidance Values of the Allowable Pressure $p_{all\,(6)}$ (kPa)

Void ratio, e	Cohensionless soils				Cohesive soils with $S \geq 0.8$							
					$I_P < 10\%$		$10\% < I_P < 20\%$			$I_P > 20\%$		
					I_C							
	Sands with gravel and coarse sands	Medium sands	Fine sands	Silty sands	0.75 – 1.00	0.25 – 0.75	0.75 – 1.00	0.50 – 0.75	0.25 – 0.50	0.75 – 1.00	0.50 – 0.75	0.25 – 0.50
0.45	670	550	415	365	410	340	540	450	–	–	–	–
0.55	545	455	395	335	325	275	420	365	–	585	–	–
0.65	430	360	270	200	220	180	340	285	240	485	405	305
0.75	–	–	180	130	–	115	265	220	170	400	350	260
0.85	–	–	–	–	–	–	240	185	130	350	285	215
0.95	–	–	–	–	–	–	170	120	75	280	225	165
1.05	–	–	–	–	–	–	–	–	50	225	170	130

Table 7
The Coefficient to Obtain the Allowable Pressure Considering the Limiting Settlement of 2 and 4 cm, [kPa]

Type of soil	s_{all} = 4 cm	s_{all} = 2 cm
Cohesionless	1.39	2.47
Cohesive with I_P < 10%	1.35	2.10
Cohesive with 10 < I_P < 20%	1.26	1.86
Cohesive with I_P > 10%	1.21	1.73

4. Conclusions

The finite element method was used for establishing the load-settlement curves and the allowable pressure for different types of soils acted by strip rigid foundations. The behaviour of the soil was modelled with the Mohr-Coulomb linear elastic-perfect plastic constitutive model implemented in the Plaxis2D software. The values of the allowable pressure corresponding to a settlement of 6 cm ($p_{all(6)}$) are lower than the values of the conventional pressures (p_{conv}), plastic pressures (p_{pl}) and the ultimate pressure (p_{ul}) obtained using the specifications from the Romanian technical regulations.

It is to be noted that the results presented in this study correspond to a rigid strip foundation with the width of 1.0 m founded at a foundation depth of 2.0 m. It is intended that these results (Table 6 and Table 7) to be used for structures and earthworks of low geotechnical complexity and risk.

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PRESIUNI ADMISIBILE PENTRU FUNDAȚII CONTINUE RIGIDE

(Rezumat)

Proiectarea fundațiilor este realizată considerând atât rezistența cât şi deformabilitatea pământului, în condițiile de încărcare preconizate. În cazul clădirilor de importanță normală, fundate pe terenuri bune de fundare proiectare poate fi realizată utilizând metode de proiectare prescriptive – compararea presiunilor efective cu presiunile admisibile. Valorile presiunilor admisibile (presiunilor convenționale), indicate în reglementările tehnice din România sunt stabilite pe baze empirice. În acest studiu sunt propuse noi valori ale presiunilor admisibile pentru fundații continue rigide, folosind o abordare numerică. Acest studiu arată că valorile presiunilor admisibile corespunzătoare unei tasări de 6 cm sunt mai mici decât valorile presiunile convenționale, plastice şi ultime obținute folosind reglementările tehnice din România.