Pile Bearing Capacity Inversion by Genetic Algorithm-Simplex

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ABSTRACT:

Pile bearing capacity inversion is complicated, and the results depend on user's empirics. In the paper, the genetic algorithm-simplex, an effective globe optimization algorithm, is applied to this inversion. Considering too many parameters and time-consuming calculations in the inversion of pile-soil model, a two-step technical route is presented, which can be implemented easily and increase the effectiveness of inversion dramatically.

KEYWORDS: Pile bearing capacity, Inversion, Genetic Algorithm-Simplex

1. PILE-SOIL MODEL

The model of Pile-Soil system shown in Figure 1 is widely used in pile capacity inversion analysis, such as CAPWAPC. In the model, the pile is dispersed to N_P elements, and at the top element, two sensors are installed, one is for measuring force $P_m(t)$, and the other is for velocity $V_m(t)$. After assuming a group of Pile-Soil parameters, we can use $P_m(t)$ as input to calculate the response of the velocity of the top of pile. If the differences between the calculated values and $V_m(t)$ are small enough to meet the threshold, the assumed parameters are considered to be real. Then, the pile capacity of pile can be obtained by the statics analysis.

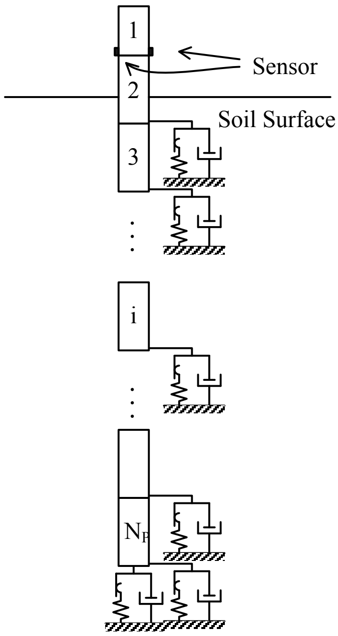
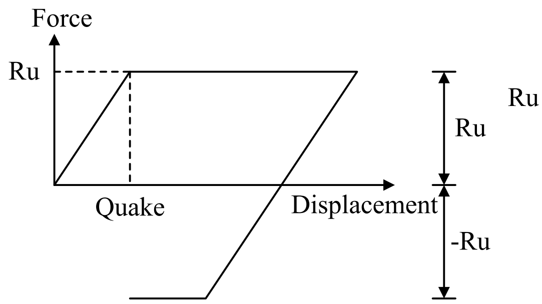
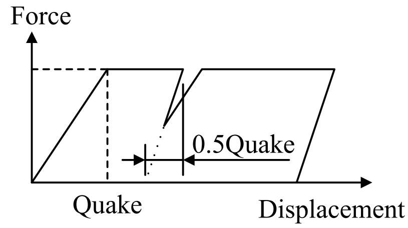


Figure 1 Model of CAPWAPC



(a) Pile side soil model



(b) Pile bottom soil model

Figure 2 Soil Model

2. CALCULATION FORMULA

During the calculation, the time interval is dispersed to $\Delta t= l/c$, where l is the length of pile, c is the wave velocity in the pile, and j to represents the time moment, i.e. $t = j\cdot\Delta t$. In the following analysis, P means force, u means upward, d means downward. Z_i means element i wave resistant, $Z_i=EA_i/c$, E is Young's modulus, A_i is the cross area of element i, $T_{u1}(i)$ and $T_{u2}(i)$ are transmission and reflection coefficient respectively.

2.1. The wave in element 1

$$\begin{bmatrix} P_u(1,j) \\ P_d(1,j) \end{bmatrix} = \begin{bmatrix} \dfrac{T_{u1}(1)}{1-T_{u2}(1)} & \dfrac{T_{u1}(1)\cdot Z_1}{1-T_{u2}(1)} \\ \dfrac{T_{u1}(1)}{1-T_{u2}(1)} & \dfrac{1}{1-T_{u2}(1)} \end{bmatrix} \begin{bmatrix} P_u(2,j-1) \\ V_m(1,j) \end{bmatrix} \tag{2.1}$$

2.2. The wave in element i ($1<i<N_P$)

$$\begin{bmatrix} P_u(i,j) \\ V(i,j) \\ S(i,j) \end{bmatrix} = \begin{bmatrix} 1-\dfrac{Z_i(1-T_{u2}(i))}{B} & \dfrac{Z_i\cdot T_{u1}(i)}{B} & \dfrac{Z_i\cdot A\cdot\Delta t}{B} & \dfrac{Z_i\cdot A}{B} \\ \dfrac{1-T_{u2}(i)}{B} & -\dfrac{T_{u1}(i)}{B} & -\dfrac{\Delta t}{2}\cdot\dfrac{A}{B} & -\dfrac{A}{B} \\ \dfrac{\Delta t}{2}\cdot\dfrac{1-T_{u2}(i)}{B} & -\dfrac{\Delta t}{2}\dfrac{T_{u1}(i)}{B} & 1-\dfrac{\Delta t^2}{4}\cdot\dfrac{A}{B} & 1-\dfrac{\Delta t}{2}\cdot\dfrac{A}{B} \end{bmatrix} \begin{bmatrix} P_d(i,j) \\ P_u(i+1,j-1) \\ V(i,j-1) \\ S(i,j-1) \end{bmatrix} + \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \tag{2.2}$$

Where A, B, C_1, C_2 and C_3 are relevant to constitutive status of element i.

2.3. The wave in element N_P

$$\begin{bmatrix} P_u(N_P,j) \\ V(N_P,j) \\ S(N_P,j) \end{bmatrix} = \begin{bmatrix} 1-Z_{N_P}\cdot\dfrac{2}{B} & Z_{N_P}\cdot\dfrac{\Delta t\cdot(A_1+A_2)}{2\cdot B} & Z_{N_P}\cdot\dfrac{A_1+A_2}{B} \\ \dfrac{2}{B} & -\dfrac{\Delta t\cdot(A_1+A_2)}{2\cdot B} & -\dfrac{A_1+A_2}{B} \\ \dfrac{\Delta t}{B} & \dfrac{\Delta t}{2}-\dfrac{\Delta t^2}{4}\cdot\dfrac{A_1+A_2}{B} & 1-\dfrac{\Delta t}{2}\cdot\dfrac{A_1+A_2}{B} \end{bmatrix} \begin{bmatrix} P_d(N_P,j) \\ V(N_P,j-1) \\ S(N_P,j-1) \end{bmatrix} + \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} + \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} \tag{2.3}$$

Where A, C_1, C_2 and C_3 are relevant to constitutive status of around element N_P, and A_2, D_1, D_2, D_3 are relevant to constitutive status of the bottom element N_P.

3. STATIC ANALYSIS

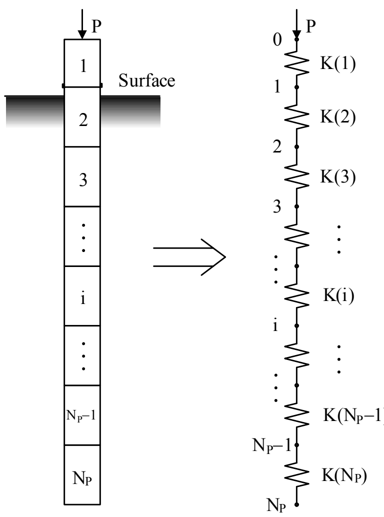


Figure 3 Static Analysis of Pile

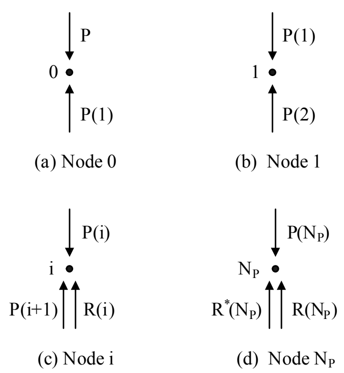


Figure 4 Node Stress

The Load-Set curve, i.e. P-S curve, is basic information that used to judge the pile capacity. In this part, P, the load at the top of pile is known, and use it to calculate the set of the pile, then the P-S curve will be obtained. During the static analysis, we use the same model, but the Visc is zero, and the elastic compression is considered.

$$[K][S]=[P][B] \tag{3.1}$$

Where,

$$[K]=\begin{bmatrix} K(1) & -K(1) & & & & & \\ -K(1) & K(1)+K(2) & -K(2) & & & & \\ & -K(2) & K(2)+K(3)+A(2) & -K(3) & & & \\ & & -K(3) & \ddots & \ddots & \ddots & \\ & & & -K(i) & K(i)+K(i+1)+A(i) & -K(i+1) & \\ & & & \ddots & \ddots & \ddots & \\ & & & & -K(N_P-1) & K(N_P-1)+K(N_P)+A(N_P-1) & -K(N_P) \\ & & & & & -K(N_P) & K(N_P)+A(N_P)+A^*(N_P) \end{bmatrix}$$

$[S]= [S(0),S(1),S(2),\ldots,S(i),\ldots S(N_P-1),S(N_P)]^T$

$[P]= [P,0,0,\ldots,0,\ldots,0,0]^T$

$[B]= [0,0,A(2),\ldots,B(i),\ldots,B(N_P-1),B(N_P)+B^*(N_P)]^T$

4. INVERSION ANALYSIS

During the inversion, the parameters (Quake, Ru and Visc) in the same soil layer are same, so if there are N_S layers around the pile, we have $3N_S$ unknown parameters, plus 3 unknown parameters of the bottom of the pile, the total parameters to be indentified are $3(N_S+1)$. According to some research, the Quake of different soils are almost same and around 0.1 inch. So, finally, the total parameters to indentify are $2N_S+4$.

The observed time length of $P_m(1,t)$ and $V_m(1,t)$ is T, time interval is Δt, total points is N_t, so $N_t=T/\Delta t$. If $V_m(1,j)$ is used as input, the calculated force of the pile at the top is $P_c(1,j)$, then the objective function F is:

$$F=\frac{\sum_{j=1}^{N_t}\left|\frac{P_m(1,j)-P_c(1,j)}{P_m(1,j)}\right|}{N_t} \tag{4.1}$$

Next, the genetic algorithm-simplex is used to inverse the parameters, and the experience is almost not required during the whole inversion.

4.1. Preliminary Estimation

In order to narrow the model space, just parts of parameters will be indentified firstly. We use the measured information before the reflection wave reaches the pile top. During this stage, the objective function F_1 is as same of (5), but the total point is q, not N_t, and $T_q=2L/c-\Delta t$, $m=cT_1/l$.

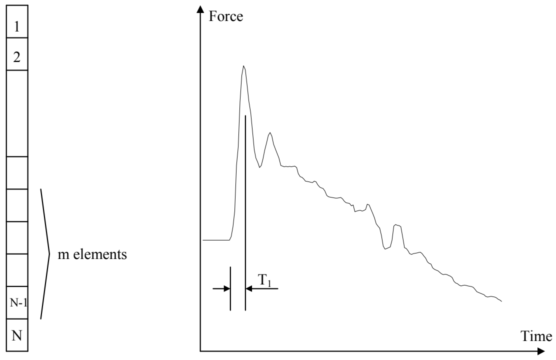


Figure 5 Number m and Time T_1

4.2. Final Estimation

During the final estimation, the parameter value range of upper elements($i=1,2,\ldots,N_P-m-1$) are the results of preliminary estimation, the parameter value range of other m+1 elements are assumed big enough base on experience.

5. EXAMPLE

The pile information in the example: steel pipe, external diameter is 27.305 cm, wall thickness is 0.77978 cm, and the length is 36 m. The elements information is shown in Table 5.1, and the measured force and velocity are shown in Figure 6, Δt=0.2 millisecond, N_t=170.

5.1. Preliminary Estimation

$$T_q = \frac{2L}{c} - \Delta t = 13.8 \ \text{millisecond}$$

$$c = \sqrt{\frac{E}{\rho}} = 5122 \text{ m/s}$$

$$q = \frac{13.8 + 3.2}{\Delta t} = 85$$

Quake: 1 - 7 millimeter,

Ru: 2×10^2 - 6×10^5 Newton

Visc: 1×10^2 - 1×10^5 Newton/m/s

T_1=0.14millisecond, $c\cdot T_1$=7.17m, m=7, N_P-m-1=28. In the calculation of optimization, group size N=200, cross probability p_c=0.6, variation probability p_m=0.05, convergence standard ε_1=0.1. We calculated 12 times, the 11st and12nd results are shown in Table 5.2.

Table 5.1 Parameters

Soil layer Number	Element Number	Mass (Kg)	Length (m)
—	1		0.60960
—	2	53.17974	1.03600
1	3–6	52.78872	1.02937
2	7–8	52.39769	1.02175
3	9–10	52.39769	1.02175
4	11–12	53.17974	1.03700
5	13–14	52.39769	1.02175
6	15–16	53.17974	1.03700
7	17–18	52.39769	1.02175
8	19–20	53.17974	1.03700
9	21–22	52.39769	1.02175
10	23–24	52.39769	1.02175
11	25–26	53.17974	1.03700
12	27–28	52.39769	1.02175
13	29–30	53.17974	1.03700
14	31–32	52.39769	1.02175
15	33–34	53.17974	1.03700
16	35–36	52.39769	1.02175
Toe	—	—	—

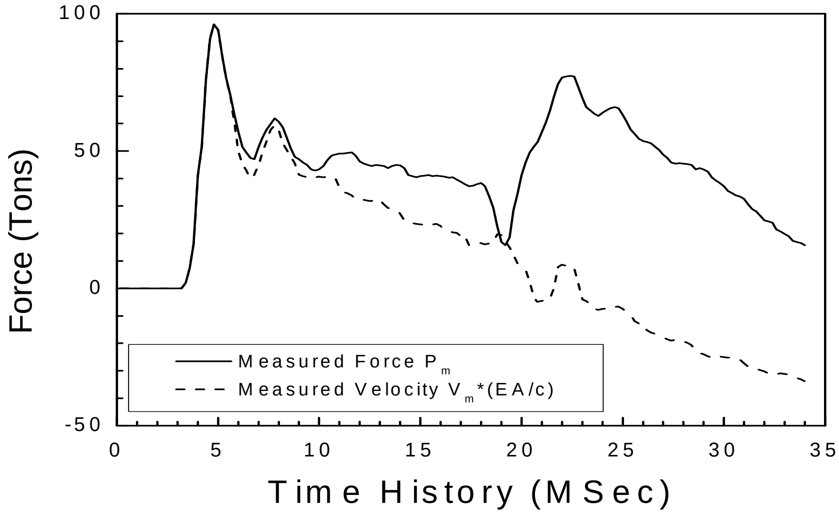


Figure 6 Measured Force and Velocity

Table 5.2 Preliminary Estimation Results

		11st			12nd		
Soil layer Number	Elements Number	Quake (m)	Ru (Newton)	Visc (N/m/s)	Quake (m)	Ru (Newton)	Visc (N/m/s)
–	1	0.000	0.000	0.000	0.000	0.000	0.000
–	2	0.000	0.000	0.000	0.000	0.000	0.000
1	3–6	3.712×10^{-3}	900.046	1928.278	3.474×10^{-3}	726.534	1301.413
2	7–8	3.712×10^{-3}	999.643	1969.087	3.474×10^{-3}	1299.792	1062.919
3	9–10	3.712×10^{-3}	1360.502	1787.384	3.474×10^{-3}	553.238	1631.228
4	11–12	3.712×10^{-3}	1670.885	1073.825	3.474×10^{-3}	438.666	1671.349
5	13–14	3.712×10^{-3}	1359.965	550.480	3.474×10^{-3}	2575.109	927.713
6	15–16	3.712×10^{-3}	14313.270	1393.288	3.474×10^{-3}	3797.365	5130.800
7	17–18	3.712×10^{-3}	5816.703	696.060	3.474×10^{-3}	1235.484	4425.541
8	19–20	3.712×10^{-3}	2850.594	6619.268	3.474×10^{-3}	1793.998	7642.656
9	21–22	3.712×10^{-3}	1842.214	3053.187	3.474×10^{-3}	2839.439	1509.748
10	23–24	3.712×10^{-3}	2253.278	4073.941	3.474×10^{-3}	4688.545	7835.827
11	25–26	3.712×10^{-3}	4028.207	4550.337	3.474×10^{-3}	2678.478	3039.443
12	27–28	3.712×10^{-3}	6526.146	1092.720	3.474×10^{-3}	11721.540	1914.700

5.2. Final Estimation

In the calculation of optimization, group size N=200, cross probability p_c=0.6, variation probability p_m=0.05, convergence standard ε_1=0.05. We calculated 12 times, the 11st and12nd results are shown in Table 5.3.

Table 5.3 Final Estimation Results

		11st			12nd		
Soil layer Number	Element Number	Quake (m)	Ru (Newton)	Visc (N/m/s)	Quake (m)	Ru (Newton)	Visc (N/m/s)
–	1	0.000	0.000	0.000	0.000	0.000	0.000
–	2	0.000	0.000	0.000	0.000	0.000	0.000
1	3–6	3.720×10^{-3}	1206.214	1296.105	3.123×10^{-3}	463.624	1622.046
2	7–8	3.720×10^{-3}	948.406	1496.860	3.123×10^{-3}	1058.914	854.674
3	9–10	3.720×10^{-3}	713.966	1568.718	3.123×10^{-3}	554.088	1420.845
4	11–12	3.720×10^{-3}	2474.114	799.877	3.123×10^{-3}	373.912	1546.388
5	13–14	3.720×10^{-3}	1408.091	427.852	3.123×10^{-3}	1419.777	897.112
6	15–16	3.720×10^{-3}	21462.680	1776.900	3.123×10^{-3}	4783.306	5042.019
7	17–18	3.720×10^{-3}	3260.015	673.507	3.123×10^{-3}	631.559	6412.517
8	19–20	3.720×10^{-3}	1702.017	3639.629	3.123×10^{-3}	1176.407	6882.972
9	21–22	3.720×10^{-3}	1211.276	3121.426	3.123×10^{-3}	1549.925	822.942
10	23–24	3.720×10^{-3}	1638.809	3223.245	3.123×10^{-3}	4472.158	9655.667
11	25–26	3.720×10^{-3}	2413.228	4869.021	3.123×10^{-3}	3387.614	3599.032
12	27–28	3.720×10^{-3}	3286.236	1539.106	3.123×10^{-3}	10018.490	1735.453
13	29–30	3.720×10^{-3}	3697.980	1627.807	3.123×10^{-3}	2406.931	596.119
14	31–32	3.720×10^{-3}	23166.520	3798.695	3.123×10^{-3}	40416.630	1706.891
15	33–34	3.720×10^{-3}	2634.276	3879.557	3.123×10^{-3}	57280.190	584.017
16	35–36	3.720×10^{-3}	115503.70	35501.91	3.123×10^{-3}	40681.530	38212.67
Toe	—	5.855×10^{-3}	372231.60	39478.60	5.735×10^{-3}	382021.50	3488.100

5.3.P-S Curve and Capacity

According to equation (3.1), we calculated 12 times, the results are shown in Table 5.4, and the calculated P-S curves are shown in Figure 7.

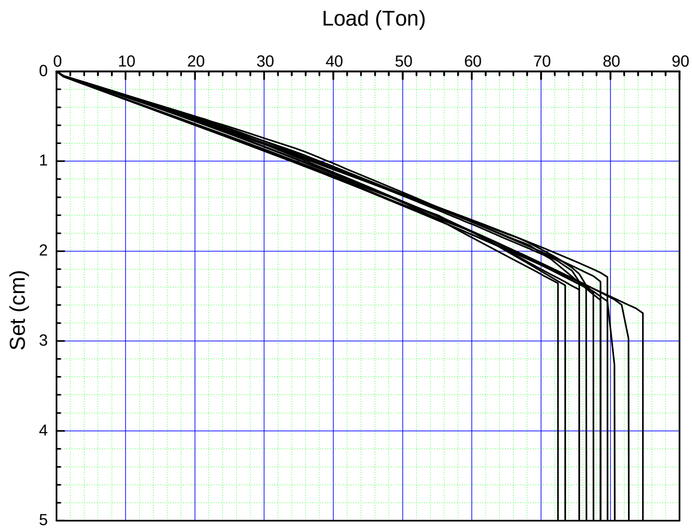


Figure 7 P-S Curve

Table 5.4 Average and RMS of Capacity

No.	1	2	3	4	5	6
Capacity (Ton)	77.55	75.51	78.57	76.53	80.61	82.56
No.	7	8	9	10	11	12
Capacity (Ton)	73.47	84.69	79.59	78.57	75.51	72.45
Average: 77.98 (Ton) Root-mean-square Error: 3.45 (Ton) Root-mean-square Error / Average: 4.42%						

6. CONCLUSIONS

Through the optimization, we have some conclusions, Firstly, the inversion results are not uniqueness. Sometimes the difference of same optimization parameter can reach several ten times. Secondly, the divergency of capacity is small and acceptable.

Furthermore, the example proves the two steps of optimization is practicable, and has high degree of accuracy, it can narrow the model space and speed up the inversion.

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