7. Application of Potential Evaluation Procedures for Liquefaction

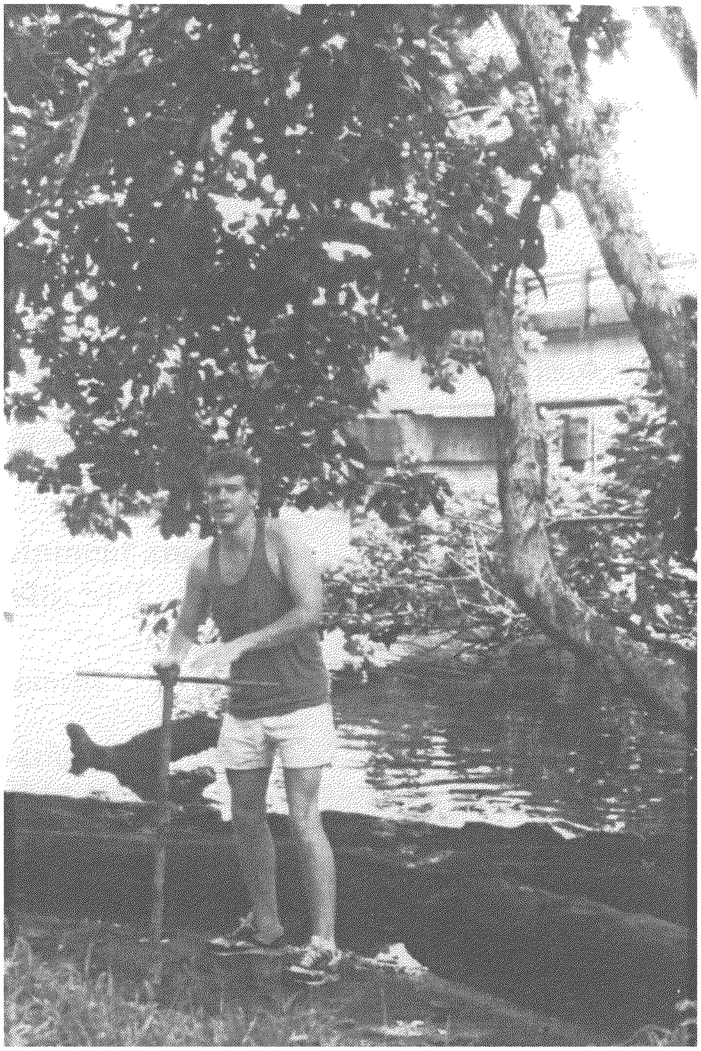


Photo 7.1 Taking soil samples

7.1 Introduction

One of the main objectives of this work has been the application of emperical methods, described in the litterature, to evaluate the potential of liquefaction on a specific site. In this chapter sites within the area affected by liquefaction due to the Limón-Telire earthquake, M = 7.6, have been investigated in order to compare the results of some empirical methods with the incidents observed during the earthquake The purpose of this comparison was to suggest a suitable method to be used when assessing the risk for liquefaction in Costa Rica in the future.

The two methods used are the ones proposed by Seed, H.B and Iwasaki, T. respectively, earlier described in *section 2.3*. These methods were chosen since they employ relatively simple procedures of calculation and estimate the soil strength from in-situ measurements (SPT-tests), thus circumventing the difficulties connected with sampling and laboratory testing. To simplify the work a spreadsheet program has been used to calculate the potential of liquefaction, i.e. the safety factors against liquefaction, on the chosen sites.

The construction of the calculations in the spreadsheet program and deviations from the theory as presented in *section 2.3* are gone through in *7.3* *Section 7.4* starts with a discussion of the used input data and continues with a presentation of the calculated safety factors site by site. The section ends with a summary and an analyse of the results.

Some of the input data used were already existing information obtained from companies and institutions in Costa Rica. Additional geotechnical data was obtained by field investigations. SPT were not a part of the field investigations, instead a so called DPL-equipment was used. Values obtained with the DPL-equipment can be transformed into correlating SPT-values. The DPL-equipment and the transformation of DPL-values into SPT-values are described in the following section, *section7.2*.

7.2 The DPL-Equipment and its Correlation With SPT

7.2.1 The DPL-Equipment

Though smaller, the principles of this german equipment is the same as for the SPT-equipment.

A steel rod is driven into the ground by the energy delivered from a 10.125 kg weight falling from a height of 50 centimeters. There is no engine to operate the weight. This has to be done by man power. Rod pieces of one meter in length are connected with screwthreads as the rod is driven deeper and deeper into the ground. The number of blows needed to penetrate ten centimeters into the ground are continously noted and called the N_{10}-value.

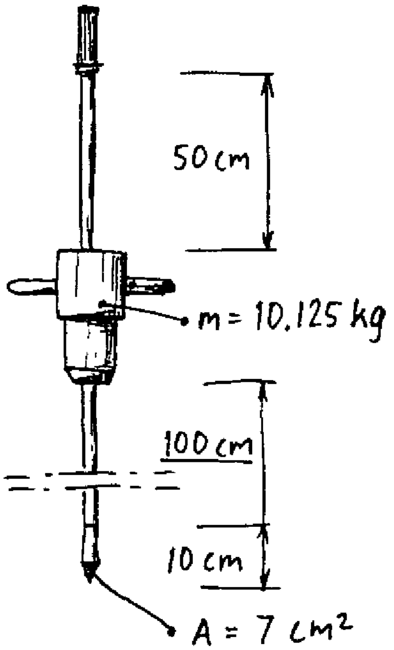


Fig 7.1 The DPL-equipment.

7.2.2 Transformation of DPL- to SPT-values, N_{10} to N_{30}

The tranformation formulas (7.1-5) are taken from the german standards (DIN 4094). Different formulas are valid in different materials and conditions of saturation. In the following, N_{10} denominates the blow count value measured in the DPL-test, while N_{30} is the corresponding SPT-value

In clay above the water table:

$$\boxed{N_{30}=0.6 \cdot N_{10}} \qquad 2 \leq N_{10} \leq 30 \qquad (7.1)$$

In clean sand above the water table (Here the transformation has to be done via another equipment, the DPH-equipment):

$$N_{10,DPH}=0.34 \cdot N_{10,DPL} \qquad 3 \leq N_{10,DPL} \leq 50 \qquad (7\ 2)$$

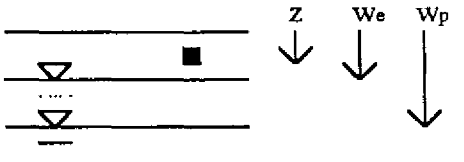
$$N_{30}=1.4 \cdot N_{10,DPH} \qquad 3 \leq N_{10,DPH} \leq 50 \qquad (7.3)$$

In clean sand, correlation between values above and below the water table:

$$N_{30,above}=1.1 \cdot N_{30,below}+5 \qquad 3 \leq N \leq 50 \qquad (7.4)$$

$$N_{10,DPL,above}=2 \cdot N_{10,DPL,below} \qquad 3 \leq N \leq 50 \qquad (7.5)$$

In the case of clean sand, the water table has to be known, both during the penetration and during the earthquake to make a correct transformation. If information is missing or to make a conservative calculation: Presume the water table low during the penetration and high during the earthquake! As the water table situation may be different during the penetration and the earthquake there are four possible cases, see *fig 7.2*!



z - depth of calculated layer

w_e - water table during earthquake

w_p - water table during penetration

CASE #1:	CASE #2:	CASE #3.	CASE #4:
$z-w_e<0$	$z-w_e \geq 0$	$z-w_e \geq 0$	$z-w_e<0$
$z-w_p<0$	$z-w_p<0$	$z-w_p \geq 0$	$z-w_p \geq 0$

Fig 7.2 Different cases of water table situations.

CASE #1 means that the calculated layer both during the earthquake and during the penetration test is above the water table. In CASE #2 the layer is below the water table during the earthquake and above it during the penetration test In CASE #3 the layer in question is below the water table both during the earthquake and during the penetration test. Finally in CASE #4, the layer is above the water table during the earthquake and below it during the penetration test.

Formula to evaluate N_{30} in CASE #1 in *fig 7.2*:

(7.3), (7.2) ⇒ $\boxed{N_{30}=0.476 \cdot N_{10}}$

Formula to evaluate N_{30} in CASE #2 in *fig 7.2*.

(7.4), (7 3), (7.2) ⇒ $\boxed{N_{30}=0.433 \cdot N_{10}-4.55}$

Formula to evaluate N_{30} in CASE #3 in *fig 7.2*·

(7.4), (7.3), (7.2), (7.5) ⇒ $\boxed{N_{30}=0.865 \cdot N_{10}-3.68}$

Formula to evaluate N_{30} in CASE #4 in *fig 7.2*:

(7.3), (7.2), (7.5) ⇒ $\boxed{N_{30}=0.952 \cdot N_{10}+0.952}$

7.3 The Seed And Iwasaki Methods as Used in This Work

7.3.1 Introduction

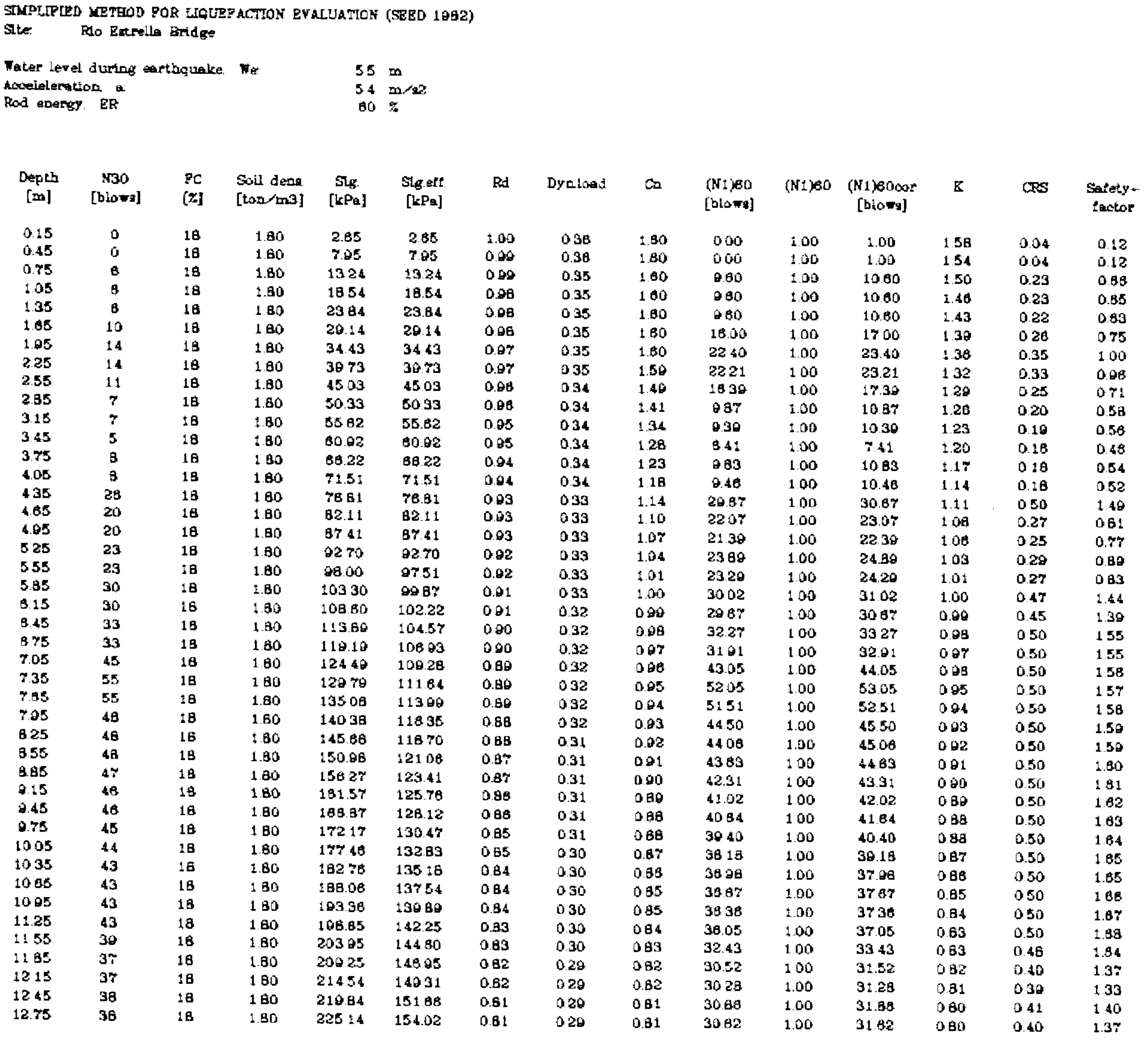
Both the Seed and the Iwasaki method make use of the SPT blow count value, N, to evaluate a soil's ability to resist liquefaction. In the SPT-test, the number of blows needed to penetrate 30 centimeters into the ground is continously noted. Thus, there is an N-value at every 30 cm from which a calculation of the liquefaction potential can be made The potential is expressed as a factor of safety, F, against liquefaction

As mentioned in the introduction to this chapter, a spreadsheet program, in Quattro Pro, has been used to facilitate the calculations.

The two following chapters describe these calculations on a rough computational form

7.3.2 Method After Seed to Determine the Potential of Liquefaction

The calculations for a site is shown in *fig. 7.3*.



SIMPLIFIED METHOD FOR LIQUEFACTION EVALUATION (SEED 1982)
Site: Rio Estrella Bridge

Water level during earthquake. We	5.5	m
Accelaleration. a	5.4	m/s2
Rod energy. ER	60	%

Depth [m]	N30 [blows]	FC [%]	Soil dens [ton/m3]	Sig. [kPa]	Sig.eff. [kPa]	Rd	Dynload	Cn	(N1)60 [blows]	(N1)60	(N1)60cor [blows]	K	CRS	Safety-factor
0.15	0	18	1.80	2.65	2.65	1.00	0.36	1.60	0.00	1.00	1.00	1.58	0.04	0.12
0.45	0	18	1.80	7.95	7.95	0.99	0.36	1.60	0.00	1.00	1.00	1.54	0.04	0.12
0.75	6	18	1.80	13.24	13.24	0.99	0.35	1.60	9.60	1.00	10.60	1.50	0.23	0.66
1.05	6	18	1.80	18.54	18.54	0.98	0.35	1.60	9.60	1.00	10.60	1.46	0.23	0.65
1.35	6	18	1.80	23.84	23.84	0.98	0.35	1.60	9.60	1.00	10.60	1.43	0.22	0.63
1.65	10	18	1.80	29.14	29.14	0.98	0.35	1.60	16.00	1.00	17.00	1.39	0.26	0.75
1.95	14	18	1.80	34.43	34.43	0.97	0.35	1.60	22.40	1.00	23.40	1.36	0.35	1.00
2.25	14	18	1.80	39.73	39.73	0.97	0.35	1.59	22.21	1.00	23.21	1.32	0.33	0.96
2.55	11	18	1.80	45.03	45.03	0.96	0.34	1.49	16.39	1.00	17.39	1.29	0.25	0.71
2.85	7	18	1.80	50.33	50.33	0.96	0.34	1.41	9.87	1.00	10.87	1.26	0.20	0.58
3.15	7	18	1.80	55.62	55.62	0.95	0.34	1.34	9.39	1.00	10.39	1.23	0.19	0.56
3.45	5	18	1.80	60.92	60.92	0.95	0.34	1.28	6.41	1.00	7.41	1.20	0.16	0.48
3.75	8	18	1.80	66.22	66.22	0.94	0.34	1.23	9.83	1.00	10.83	1.17	0.18	0.54
4.05	8	18	1.80	71.51	71.51	0.94	0.34	1.18	9.46	1.00	10.46	1.14	0.18	0.52
4.35	26	18	1.80	76.81	76.81	0.93	0.33	1.14	29.67	1.00	30.67	1.11	0.50	1.49
4.65	20	18	1.80	82.11	82.11	0.93	0.33	1.10	22.07	1.00	23.07	1.08	0.27	0.81
4.95	20	18	1.80	87.41	87.41	0.93	0.33	1.07	21.39	1.00	22.39	1.06	0.25	0.77
5.25	23	18	1.80	92.70	92.70	0.92	0.33	1.04	23.89	1.00	24.89	1.03	0.29	0.89
5.55	23	18	1.80	98.00	97.51	0.92	0.33	1.01	23.29	1.00	24.29	1.01	0.27	0.83
5.85	30	18	1.80	103.30	99.87	0.91	0.33	1.00	30.02	1.00	31.02	1.00	0.47	1.44
6.15	30	18	1.80	108.60	102.22	0.91	0.32	0.99	29.67	1.00	30.67	0.99	0.45	1.39
6.45	33	18	1.80	113.89	104.57	0.90	0.32	0.98	32.27	1.00	33.27	0.98	0.50	1.55
6.75	33	18	1.80	119.19	106.93	0.90	0.32	0.97	31.91	1.00	32.91	0.97	0.50	1.55
7.05	45	18	1.80	124.49	109.28	0.89	0.32	0.96	43.05	1.00	44.05	0.96	0.50	1.56
7.35	55	18	1.80	129.79	111.64	0.89	0.32	0.95	52.05	1.00	53.05	0.95	0.50	1.57
7.65	55	18	1.80	135.08	113.99	0.89	0.32	0.94	51.51	1.00	52.51	0.94	0.50	1.58
7.95	48	18	1.80	140.38	116.35	0.88	0.32	0.93	44.50	1.00	45.50	0.93	0.50	1.59
8.25	48	18	1.80	145.68	118.70	0.88	0.31	0.92	44.06	1.00	45.06	0.92	0.50	1.59
8.55	48	18	1.80	150.98	121.06	0.87	0.31	0.91	43.63	1.00	44.63	0.91	0.50	1.60
8.85	47	18	1.80	156.27	123.41	0.87	0.31	0.90	42.31	1.00	43.31	0.90	0.50	1.61
9.15	46	18	1.80	161.57	125.76	0.86	0.31	0.89	41.02	1.00	42.02	0.89	0.50	1.62
9.45	46	18	1.80	166.87	128.12	0.86	0.31	0.88	40.64	1.00	41.64	0.88	0.50	1.63
9.75	45	18	1.80	172.17	130.47	0.85	0.31	0.88	39.40	1.00	40.40	0.88	0.50	1.64
10.05	44	18	1.80	177.46	132.83	0.85	0.30	0.87	38.16	1.00	39.16	0.87	0.50	1.65
10.35	43	18	1.80	182.76	135.18	0.84	0.30	0.86	36.98	1.00	37.98	0.86	0.50	1.65
10.65	43	18	1.80	188.06	137.54	0.84	0.30	0.85	36.67	1.00	37.67	0.85	0.50	1.66
10.95	43	18	1.80	193.36	139.89	0.84	0.30	0.85	36.36	1.00	37.36	0.84	0.50	1.67
11.25	43	18	1.80	198.65	142.25	0.83	0.30	0.84	36.05	1.00	37.05	0.83	0.50	1.68
11.55	39	18	1.80	203.95	144.60	0.83	0.30	0.83	32.43	1.00	33.43	0.83	0.46	1.54
11.85	37	18	1.80	209.25	146.95	0.82	0.29	0.82	30.52	1.00	31.52	0.82	0.40	1.37
12.15	37	18	1.80	214.54	149.31	0.82	0.29	0.82	30.28	1.00	31.28	0.81	0.39	1.33
12.45	38	18	1.80	219.84	151.66	0.81	0.29	0.81	30.86	1.00	31.86	0.80	0.41	1.40
12.75	38	18	1.80	225.14	154.02	0.81	0.29	0.81	30.62	1.00	31.62	0.80	0.40	1.37

Fig. 7.3 Calculation of safety factors against liquefaction for a site. Method after Seed.

Input

for the hole profile

- Water table during penetration test, $\mathbf{w_p}$ (m) (when using DPL-values)
- Water table during earthquake, $\mathbf{w_e}$ (m)
- Horizontal acceleration at surface, **a** (m/s2)
- Delivered Rod Energy from SPT-equipment, $\mathbf{ER_m}$ (%)

for each level:

- Depth under surface, **z** (m)
- SPT or DPL blowcount value, $\mathbf{N_{30}}$ or $\mathbf{N_{10}}$ (blows)
- Contents of fines (D<0.074 mm), **FC** (%)
- Soil Density, ρ_s (ton/m3)

Calculations

at each level:

If N_{10} is given as input the corresponding N_{30}-values must be calculated (compare *section 7 2.2*)

$\mathbf{N_{30}}$, blows:

```
If $FC>98$
    then $N_{30}=0.6 \cdot N_{10}$
else if $z-w_e<0$ and $z-w_p<0$
    then $N_{30}=0\ 476 \cdot N_{10}$
else if $z-w_e \geq 0$ and $z-w_p<0$
    then $N_{30}=0.433 \cdot N_{10}-4.55$
else if $z-w_e \geq 0$ and $z-w_p \geq 0$
    then $N_{30}=0.865 \cdot N_{10}-3.68$
else if $z-w_e<0$ and $z-w_p \geq 0$
    then $N_{30}=0\ 952 \cdot N_{10}+0.952$
else $N_{30}=0$

If $N_{30}<1$
    then $N_{30}=1$
```

σ_0, vertical overburden pressure.

$$\sigma_{0,n}=\sigma_{v,n-1}+\rho_s(z_n-z_{n-1})g$$

where n denotes the number of the calculated layer, the layers being numbered from top of profile to bottom.

σ_0', effective overburden pressure:

$$\sigma_0'=\sigma_0-\rho_w \cdot w_e \cdot g$$

where ρw is the density of water

r_d, reduction factor for soil stiffnes:

$$r_d=1-0.015z$$

We are now able to calculate the cyclic load induced by the earthquake.

τ_{av}/σ_v', cyclic load:

$$\frac{\tau_{av}}{\sigma_0'}=0.65\;\frac{a}{g}\,\frac{\sigma_0}{\sigma_0'}\,r_d$$

Continuing with the correction of the N_{30}-value

c_n, correction due to the effective overburden pressure:

$$c_n=\frac{1}{\sqrt{\sigma_0'/100}}$$

Finally the soil resistance is calculated and corrected for the influence of effective overburden pressure.

$(N_1)_{60}$, N_{30}-value corrected with c_n, and the fraction of energy delivered to the drill rod in the SPT-test, ER_m:

$$(N_1)_{60}=c_n\,\frac{ER_m}{60}\,N_{30}$$

Having established the (N1)60-value we make the correction for fine contents:

Δ(N1)60, correction for fine contents:

```
If $FC<10\%$
        then $\Delta(N1)60=0$
else if $FC<25\%$
        then $\Delta(N1)60=1$
else if $FC<50\%$
        then $\Delta(N1)60=2$
else if $FC<75\%$
        then $\Delta(N1)60=4$
else $\Delta(N1)60=5$
```

(N1)60corr, corrected (N1)60-value:

$$(N1)60corr=(N1)60+\Delta(N1)60$$

The soil resistance, CRS, is calculated and corrected for the influence of effective overburden pressure

K_σ, correction for overburden pressure in resistance to cyclic loading (compare curve in *fig. 2.14*):

$$K_\sigma = 1.6 - 0.007637 \cdot \sigma_0' + 0.000017687 \cdot \sigma_0'^{\,2} - 0.000000013 \cdot \sigma_0'^{\,3}$$

CRS, in-situ resistence (compare curve for M=7.5 in *fig. 2.12*):

$$CRS = (0.028234 \cdot (N1)_{60corr} - 0.001724 (N1)_{60corr}^{\,2} + 0.000042 \cdot (N1)_{60corr}^{\,3}) \cdot K_\sigma$$

The factor of safety is finally calculated as the quotient of the soil strength and the cyclic load

Output

for each level:

F, factor of safety.

$$F = \frac{CRS}{\tau_{av} / \sigma_0'}$$

Since the sites investigated in this work corresonded to level ground, or where considered to possess small static shear stresses, no correction for initial shear stresses has been made in the calculations.

7.3.3 Method After Iwasaki to Determine the Potential of Liquefaction

Fig. 7.4 shows a calculation for a site using the method after Iwasaki.

SOIL LIQUEFACTION POTENTIAL EVALUATION (Iwasaki et al. 1978)
Site: Rio Estrela Bridge

Water level	5.5	m
Final depth	13	m
Hor. acc.	5.4	m/s2

Depth (m)	N	D50 (mm)	FC (%)	R1	R2	R3	Rtot	Dens	Sig. (kPa)	Sig.eff (kPa)	rd	Dyn.load	FL (Safetyf.)
0.15	0	0.140	18	0.00	0.09	0.00	0.09	1.80	2.65	2.65	1.00	0.55	0.16
0.45	0	0.140	18	0.00	0.09	0.00	0.09	1.80	7.95	7.95	0.99	0.55	0.16
0.75	6	0.140	18	0.24	0.09	0.00	0.33	1.80	13.24	13.24	0.99	0.54	0.60
1.05	6	0.140	18	0.23	0.09	0.00	0.32	1.80	18.54	18.54	0.98	0.54	0.59
1.35	6	0.140	18	0.22	0.09	0.00	0.31	1.80	23.84	23.84	0.98	0.54	0.58
1.65	10	0.140	18	0.28	0.09	0.00	0.37	1.80	29.14	29.14	0.98	0.54	0.69
1.95	14	0.140	18	0.32	0.09	0.00	0.41	1.80	34.43	34.43	0.97	0.53	0.77
2.25	14	0.140	18	0.32	0.09	0.00	0.40	1.80	39.73	39.73	0.97	0.53	0.76
2.55	11	0.140	18	0.27	0.09	0.00	0.36	1.80	45.03	45.03	0.96	0.53	0.68
2.85	7	0.140	18	0.21	0.09	0.00	0.30	1.80	50.33	50.33	0.96	0.53	0.57
3.15	7	0.140	18	0.21	0.09	0.00	0.30	1.80	55.62	55.62	0.95	0.52	0.57
3.45	5	0.140	18	0.17	0.09	0.00	0.26	1.80	60.92	60.92	0.95	0.52	0.50
3.75	8	0.140	18	0.21	0.09	0.00	0.30	1.80	66.22	66.22	0.94	0.52	0.58
4.05	8	0.140	18	0.21	0.09	0.00	0.30	1.80	71.51	71.51	0.94	0.52	0.58
4.35	26	0.140	18	0.37	0.09	0.00	0.46	1.80	76.81	76.81	0.93	0.51	0.90
4.65	20	0.140	18	0.32	0.09	0.00	0.41	1.80	82.11	82.11	0.93	0.51	0.80
4.95	20	0.140	18	0.31	0.09	0.00	0.40	1.80	87.41	87.41	0.93	0.51	0.79
5.25	23	0.140	18	0.33	0.09	0.00	0.42	1.80	92.70	92.70	0.92	0.51	0.83
5.55	23	0.140	18	0.33	0.09	0.00	0.42	1.80	98.00	97.51	0.92	0.51	0.82
5.85	30	0.140	18	0.37	0.09	0.00	0.46	1.80	103.30	99.87	0.91	0.52	0.89
6.15	30	0.140	18	0.37	0.09	0.00	0.46	1.80	108.60	102.22	0.91	0.53	0.86
6.45	33	0.140	18	0.38	0.09	0.00	0.47	1.80	113.89	104.57	0.90	0.54	0.87
6.75	33	0.140	18	0.38	0.09	0.00	0.47	1.80	119.19	106.93	0.90	0.55	0.85
7.05	45	0.140	18	0.44	0.09	0.00	0.53	1.80	124.49	109.28	0.89	0.56	0.95
7.35	55	0.140	18	0.49	0.09	0.00	0.57	1.80	129.79	111.64	0.89	0.57	1.01
7.65	55	0.140	18	0.48	0.09	0.00	0.57	1.80	135.08	113.99	0.89	0.58	0.99
7.95	48	0.140	18	0.45	0.09	0.00	0.54	1.80	140.38	116.35	0.88	0.58	0.92
8.25	48	0.140	18	0.44	0.09	0.00	0.53	1.80	145.68	118.70	0.88	0.59	0.90
8.55	48	0.140	18	0.44	0.09	0.00	0.53	1.80	150.98	121.06	0.87	0.60	0.89
8.85	47	0.140	18	0.43	0.09	0.00	0.52	1.80	156.27	123.41	0.87	0.60	0.87
9.15	46	0.140	18	0.43	0.09	0.00	0.52	1.80	161.57	125.76	0.86	0.61	0.85
9.45	46	0.140	18	0.42	0.09	0.00	0.51	1.80	166.87	128.12	0.86	0.62	0.84
9.75	45	0.140	18	0.42	0.09	0.00	0.51	1.80	172.17	130.47	0.85	0.62	0.82
10.05	44	0.140	18	0.41	0.09	0.00	0.50	1.80	177.46	132.83	0.85	0.62	0.80
10.35	43	0.140	18	0.40	0.09	0.00	0.49	1.80	182.76	135.18	0.84	0.63	0.78
10.65	43	0.140	18	0.40	0.09	0.00	0.49	1.80	188.06	137.54	0.84	0.63	0.78
10.95	43	0.140	18	0.40	0.09	0.00	0.49	1.80	193.36	139.89	0.84	0.64	0.77
11.25	43	0.140	18	0.40	0.09	0.00	0.49	1.80	198.65	142.25	0.83	0.64	0.76
11.55	39	0.140	18	0.38	0.09	0.00	0.47	1.80	203.95	144.60	0.83	0.64	0.73
11.85	37	0.140	18	0.36	0.09	0.00	0.45	1.80	209.25	146.95	0.82	0.64	0.70
12.15	37	0.140	18	0.36	0.09	0.00	0.45	1.80	214.54	149.31	0.82	0.65	0.70
12.45	38	0.140	18	0.37	0.09	0.00	0.45	1.80	219.84	151.66	0.81	0.65	0.70
12.75	38	0.140	18	0.36	0.09	0.00	0.45	1.80	225.14	154.02	0.81	0.65	0.70

Fig. 7.4 Calculation of safety factors against liquefaction. Method after Iwasaki.

Input

for the hole profile:

- Water table during penetration test, $\mathbf{w_p}$ (m)
- Water table during earthquake, $\mathbf{w_e}$ (m)
- Horizontal acceleration at surface, **a** (m/s2)

for each level:

- Depth under surface, **z** (m)
- SPT or DPL blowcount value, $\mathbf{N_{30}}$ or $\mathbf{N_{10}}$ (blows)
- Mean particle diameter, $\mathbf{D_{50}}$ (mm)
- Contents of fines (D less then 0.074 mm), **FC** (%)
- Saturated soil density, $\boldsymbol{\rho_s}$ (ton/m3)

Calculations

at each level:

$\mathbf{N_{30}}$, blows (If N_{10} is given as input):

```
If $D_{50} < 0.002$
    then $N_{30}=0.6*N_{10}$
else if $z-w_e<0$ and $z-w_p<0$
    then $N_{30}=0.476*N_{10}$
else if $z-w_e\geq 0$ and $z-w_p<0$
    then $N_{30}=0.433*N_{10}-4.55$
else if $z-w_e\geq 0$ and $z-w_p\geq 0$
    then $N_{30}=0.865*N_{10}-3.68$
else if $z-w_e<0$ and $z-w_p\geq 0$
    then $N_{30}=0.952*N_{10}+0.952$
else $N_{30}=0$

If $N_{30}<1$
    then $N_{30}=1$
```

$\boldsymbol{\sigma_0}$, vertical overburden pressure:

$$\sigma_{0,n}=\sigma_{0,n-1}+\rho_s(z_n-z_{n-1})g$$

n being the number of the layer in question.

$\boldsymbol{\sigma_0'}$, effective overburden pressure:

$$\sigma_0'=\sigma_0-\rho_w*w_e*g$$

Now the soil strength, or resistance to liquefaction, can be calculated.

R_1, in-situ recistance:

$$R_1 = 0.0882\sqrt{\frac{N_{30}}{\sigma_0' + 0.7}}$$

R_2, in-situ resistance.

```
If $D_{50} \leq 0.05$
    then $R_2 = 0.19$
else if $D_{50} \leq 0.6$
    then $R_2 = 0.225\log(0.35/D_{50})$
else $R_2 = -0.05$
```

R_3, in-situ resistence:

```
If $FC < 40$
    then $R_3 = 0$
else $R_3 = 0.04*FC - 0.16$
```

R_t, total in-situ resistance.

$$R_t = R_1 + R_2 + R_3$$

L, dynamic load:

$$L = \frac{a}{g}\,\frac{\sigma_0}{\sigma_0'}\,(1-0.015z)$$

F_l, factor of safety:

$$F_l = \frac{R_t}{L}$$