MYANMAR GEOLOGISTS SOCIETY SINGAPORE

The MGSS Technical Seminar No. 4

IS SINGAPORE SAFE FROM EARTHQUAKES IN SUMATRA, INDONESIA?

A geotechnical investigative approach of potential effects on foundation in reclaimed areas

By

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Geotectonic setting of Singapore assures that Singapore is situated in aseismic zone.

It is located behind the back arc basin of the Sunda Mega Thrust (subduction zone) and on the continent, the Malay Peninsula. Therefore, it is safe in terms of earthquake hazards.

However, whenever there was a big earthquake ($Mw \geq 8.0$) occurred either along the Sunda Mega Thrust or along Sunda Right-lateral Strike Slip Fault tremors could be felt in Singapore.

People are concerned of the safety while residing in tall buildings.

Shakes due to earthquakes do not have destructive effects in hard rocks but it does in soft rocks and particularly in unconsolidated sediments which has low shear wave velocities.

Therefore, there is a geotechnical concern that sand fills in reclaimed areas might be susceptible to earthquake shear waves.

In Singapore reclaimed land forms extensive unconfined aquifers. Sand layers of varying thickness from 12 to 18 m are fully saturated and thus favouring liquefaction in foundation during the time of earthquakes.

CONCERN

On December 4, 2010 The Straits Times senior correspondent Christopher Tan reported that **"Just how vulnerable buildings in Singapore will be to tremors from major earthquakes in the region is still being investigated".**

It was also reported that following the massive quakes that devastated nearby Sumatra in 2004, 2005 and 2007 two studies were commissioned two years ago.

One study is by the Building and Construction Authority (BCA).

Nanyang Technological University (NTU) was commissioned to conduct an "earthquake vulnerability" study. This study may take another year to complete (The Straits Times, page B6, December 4, 2010).

The Housing Board (HDB) engaged the National University of Singapore (NUS) to develop "cost-effective monitoring sensors" to be mounted on HDB blocks.

The sensors will enable inspections in the event of tremors but not to assess the vulnerability of buildings to tremor.

Earthquakes

Keppel Land

Singapore is not safe from regional earthquakes as more high-rise buildings are built on reclaimed land and building codes do not factor in earthquake design and standards

Stephen Chew, Keppel Land International, December 2010

THE QUESTION

"Whether Singapore's construction codes may need to include provisions for tremors".

Such consideration had never occurred before since Singapore was long earthquake free.

According to the Straits Times, Professor Koh Chan Ghee, NUS Centre for Hazards Research, told that
"*it is not uncommon for building codes to be revised, if necessary, given that a big earthquake is a low-probability but high-consequence event*".

AREAS OF CONCERN

Assistant **Professor** Kusnowidjaja **Megawati** of EOS said that

"the real worry for Singapore is for buildings which stand on marine clay and some reclaimed land. These soil types tend to amplify low-frequency vibrations from earthquakes hundreds of kilometers away".

Such soft soils form about a quarter of Singapore's land particularly in the southeast.

A generalized geological map of Singapore showing the occurrence of the Kallang Formation (prepared by Singapore Straits Times, 2010)

Professor Megawati noted that in the 8.4 magnitude Sumatran earthquake in 2007 the ground acceleration was 3.0 cm/s2 (0.003g) in Kallang (**soft soil**) and less than 1.0 cm/s2 (0.001g) in Bukit Timah (**hard rock**).

It was also noted that buildings as far inland as Toa Payoh and Little India shook. Thus, effect could be much higher for "the next big one".

Recent simulations have shown that an 8.8-magnitude in Sumatra would create "***ground acceleration of 10 cm/s2 in Bukit Timah (hard rock) and 30 to 40 cm/s2 in the Kallang Formation***".

However, more study is required to agree on the extent of Singapore's risk exposure to earthquakes in Sumatra.

RECENT EARTHQUAKES IN SUMATRA

Sumatra is the regional hotspot of Southeast Asia.

In 2004, Mw 9.0 earthquake located in the Indian Ocean off the west coast of Sumatra triggered "the killer tsunami" that killed 180,000 in Aceh.

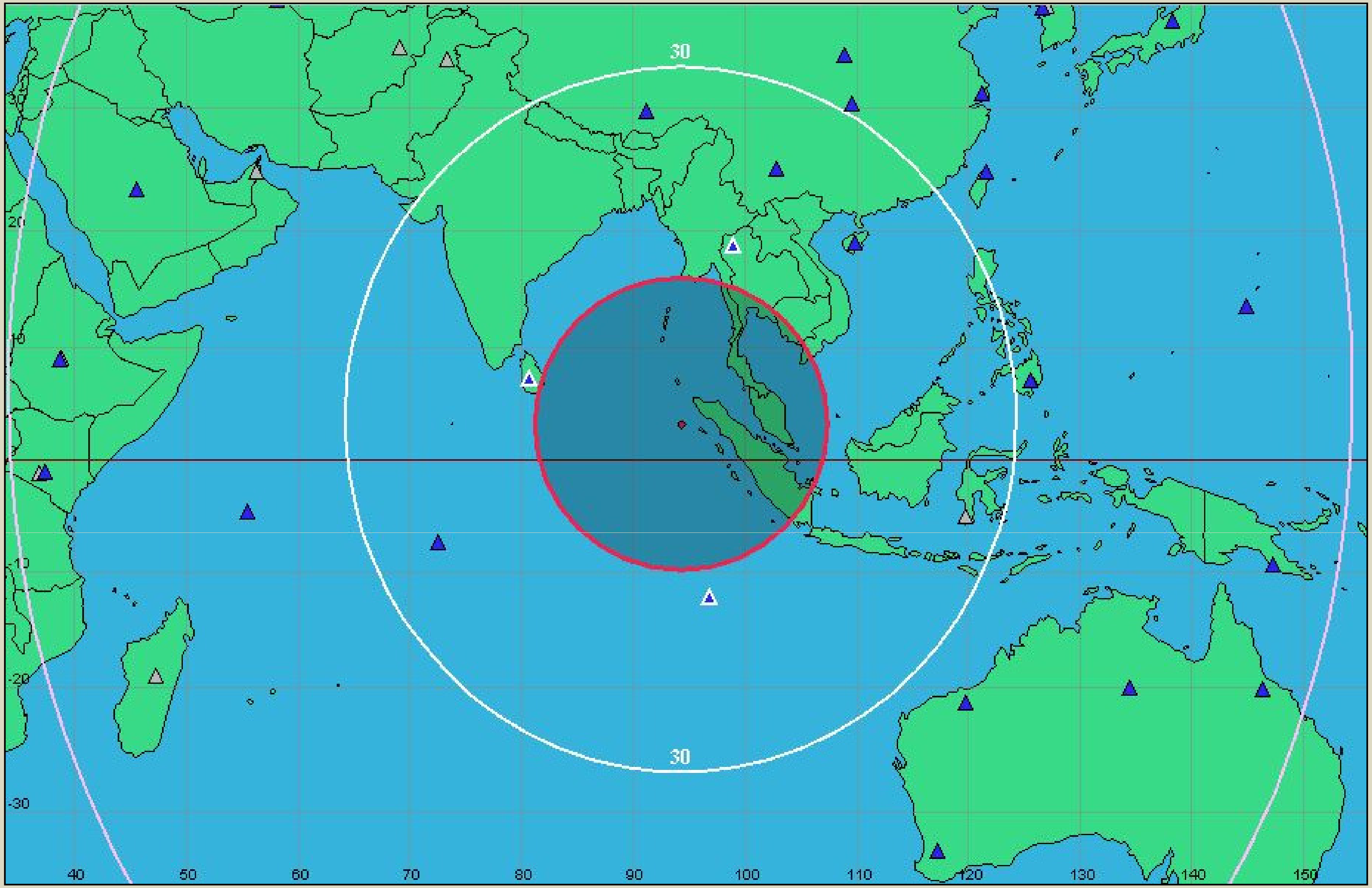
It was one of the deadliest natural disasters in recorded history. Indonesia was hardest hit followed by Sri Lanka, India and Thailand.

In March 2005, northern part of Sumatra was hit by Mw 8.7 earthquake killing 1300 people on the island of Nias.

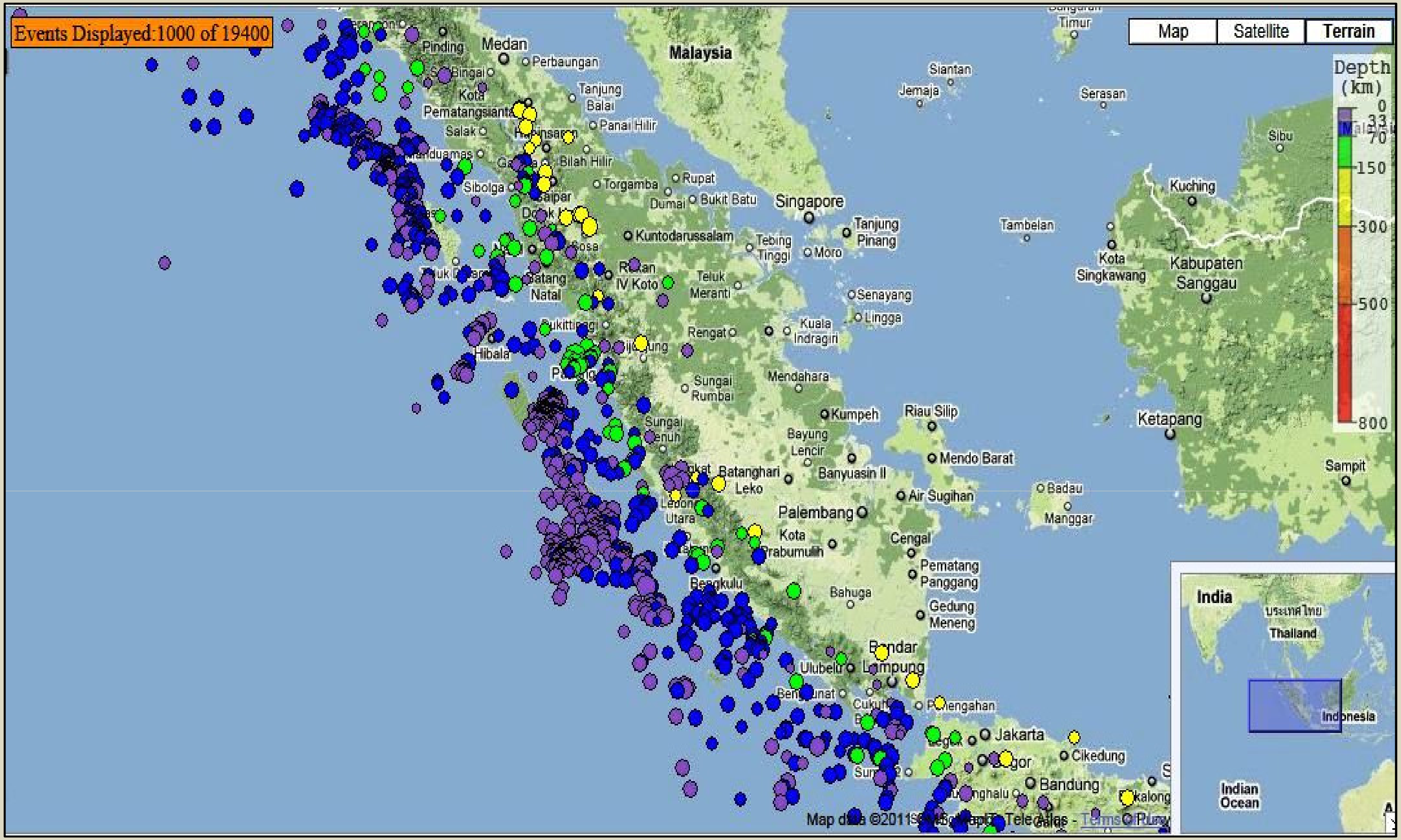
In September 2006, West Java was hit by Mw 6.8 earthquake creating tsunami to kill 660 people.

In September 2009, Padang was struck by Mw 7.6 earthquake killing 1100 people.

In 2010, Mw 7.5 earthquake was the cause of 4-m high tsunami that swept away homes in the Metawai Islands, off West Sumatra province. About 460 people were killed.



Event: Off West Coast of Northern Sumatra. 26 December 2004. 00:58:050GMT. Mw 9.0. Depth 28.6km. Latitude 3.09, Longitude 94.26.



Earthquakes in Sumatra up to April 2011

Major Sources of Earthquakes

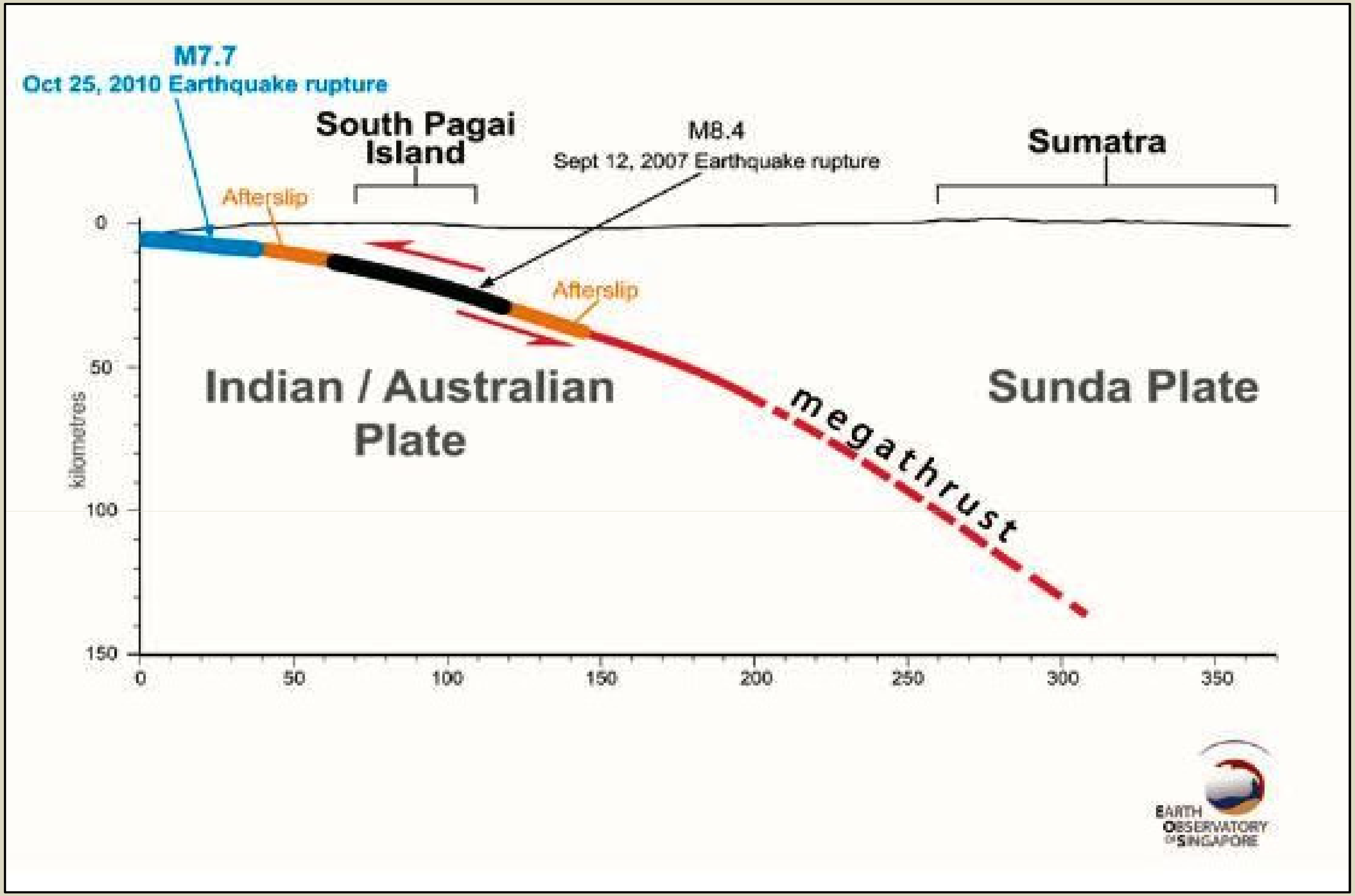
Sumatran subduction zone and seismicity

The Sumatran subduction zone is a Megathrust formed by underthrusting of the Indian-Australian Plate beneath the Sunda Plate (Eurasian Plate).

The shortest distance from the subduction zone to Singapore is about 600 km. Earthquakes occurred in the subduction zone are generated at shallow to intermediate depths (i.e. < 50 km).

Historical records reveal that over last 300 years there were four great earthquakes in this zone.

Year	Magnitude, Mw	Reference / Remarks	
1833	**8.75**	Newcomb & McCann (1987)	In Balendra & Li (2008)
1861	**8.40**		
2004 December	**9.30**	Aceh, 30 km depth	950km from Singapore
2005 March	**8.7**	Nias, 32 km depth	>600 km from Singapore



Schematic diagram of Sunda Megathrust by EOS

Sumatran Strike Slip Fault

This dextral strike slip fault is the second source of earthquakes and it extends along the entire length of Sumatra (>1500 km).

It is about 400 km away from Singapore. This is shear deformation of rocks in the continental crust.

The energy released from this fault is at lower stress level compared to that of the Sumatran subduction zone.

The maximum magnitude of this fault may not exceed Mw 7.8 (Merati et al., 2000 and Balendra et al., 2002 in Balendra & Li, 2008).

Year	Magnitude, Mw	Reference
1892	**7.7**	Prawirodirdjo et al., 2000; Sieh & Natawidjara, 2000

When is the big one?

Dr Wahyu Triyoso of the Bandung Institute of Technology predicts that there will be ***at least one major earthquake in near future.***

Prof. Hery predicted that ***next big one would be off the Mentawai Islands and will measure well above a magnitude of 8.*** (The Straits Times, March 25 2011, p.B6). He added, “We now know where it’s going to be but when”.

Professor Kerry Sieh, the director of NTU’s Earth Observatory of Singapore, predicts that ***a quake of magnitude 8.8 will hit north of Padang in Sumatra within next few decades*** (The Straits Times, December 4, 2010).

Mentawai islands: the predicted next big one.

According to Sun and Pan (1995a; 1995b), the recurrence interval of an earthquake a moment magnitude of 8.5 or larger would be about 340 years.

It was based on the probabilistic seismic hazard analysis of the Sumatran subduction zone and corresponds to a 14% probability of exceedance within 50 years.

Balendra et al. (2002) identified the worst earthquake scenario along subduction zone as Mw 8.9.

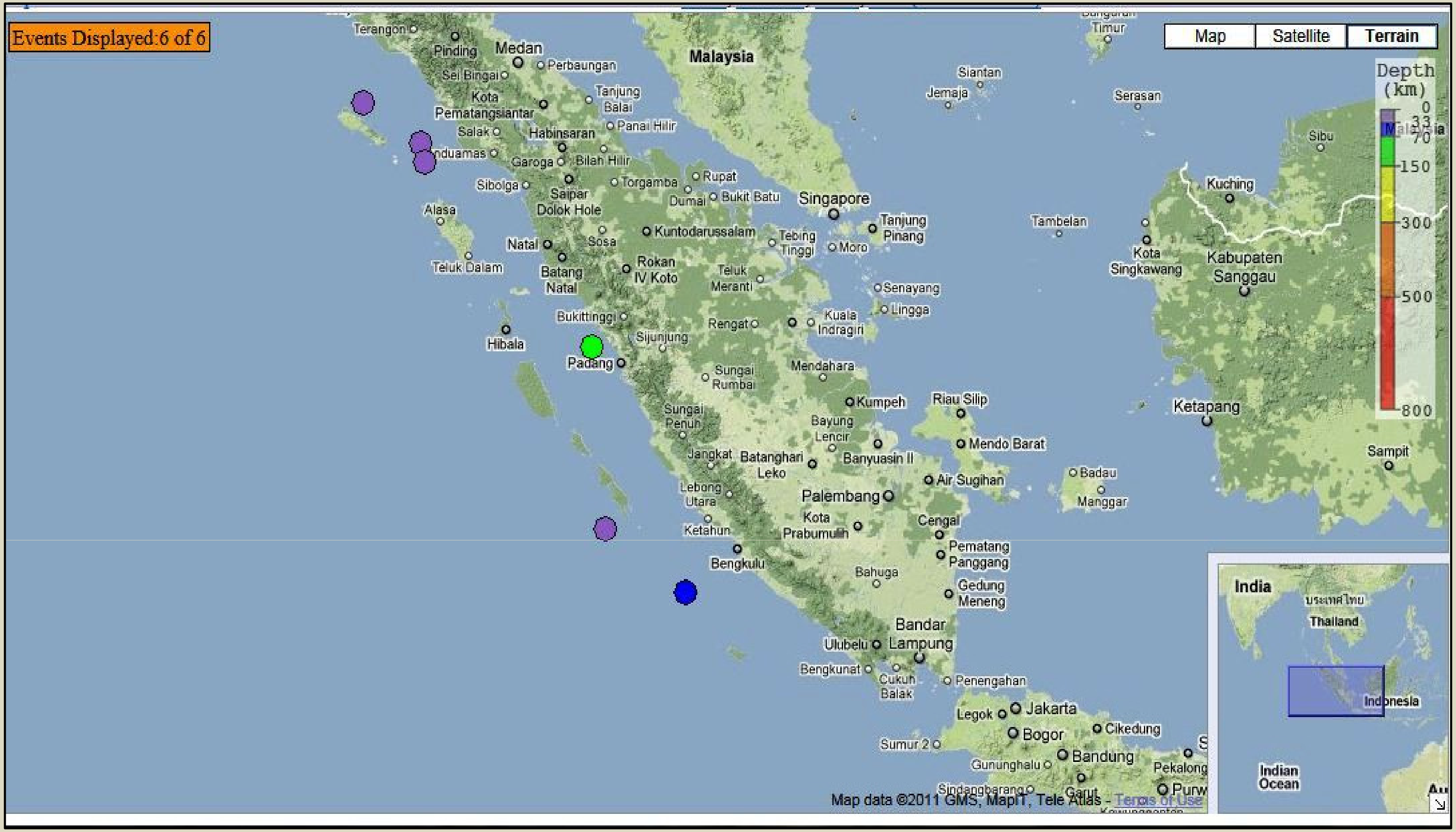
Megawati and Pan (2002) recognized the 1833 Sumatran subduction earthquake (Mw 8.75) as the worst scenario earthquake.

However, Aceh earthquake (Mw 9.3) in 2004 exceeded those numbers. Epicenter was 950 km away from Singapore.

Between2002 and 2010, recorded earthquakes generated along the subduction zone have the magnitude ranging from 7.6 to *8.3*
(moment magnitude & surface waves)

Magnitude ▼	Depth (km)	Time	Lat	Lon	Mag. Type	Mag. Contrib.	Event Source	Catalog
7.53	31.0	2002/11/02 01:26:11.8300	2.9794	96.1147	MS	ISC	ISC	ISCCD
7.6	81.0	2009/09/30 10:16:09.2500	-0.72	99.867	MW	GCMT	NEIC	MHDF
7.8	20.1	2010/10/25 14:42:22.4600	-3.487	100.082	MW	GCMT	NEIC	WHDF
7.8	31.0	2010/04/06 22:15:01.5800	2.383	97.048	MW	GCMT	NEIC	WHDF
8.36	30.0	2005/03/28 16:09:35.2900	2.0964	97.1131	MS	ISC	ISC	ISCCD
8.37	35.5	2007/09/12 11:10:26.8700	-4.4636	101.396	MS	ISC	ISC	ISCCD

http://www.iris.edu/servlet/eventserver/eventsHTML.do?MagMin=7.5&MagMax=10&priority=size&PointsMax=1000&LatMax=4.98&LatMin=-7.19&LonMax=115.14&LonMin=89.98



Mw 7.5 to 8.5 earthquakes, off western coast of Sumatra, up to April 2011. Note: Mw 7.5 Padang earthquake on 30 September 2009.(IRIS, VASE2.9).

GEOTECTNICAL ASPECT

In Singapore reclaimed land forms extensive unconfined aquifers.

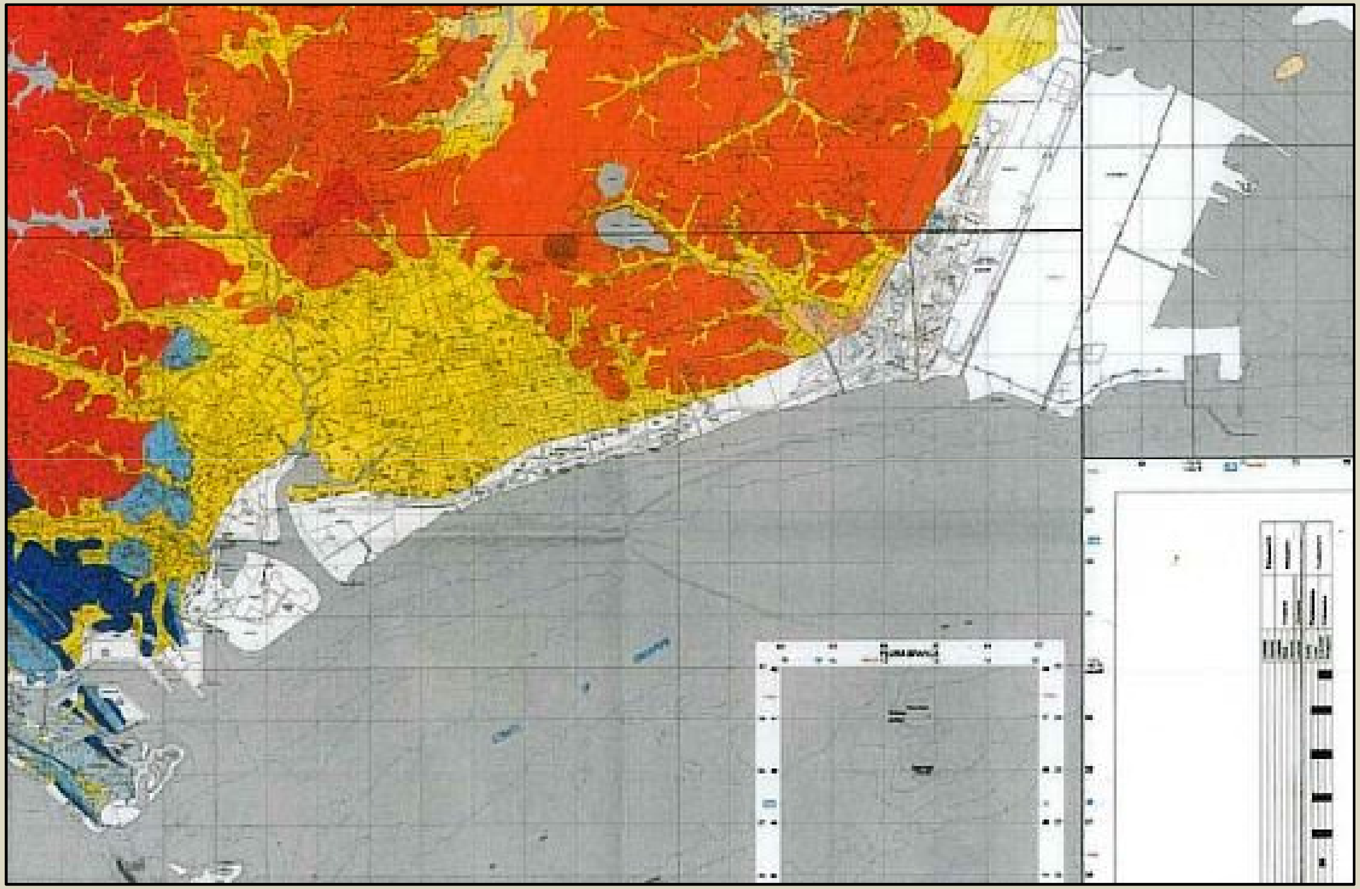
Sand layers of varying thickness from 12 to 18 m are fully saturated and thus favouring liquefaction in foundation during the time of earthquakes.

Liquefaction

Soil liquefaction and related ground failures are commonly associated with large earthquakes.

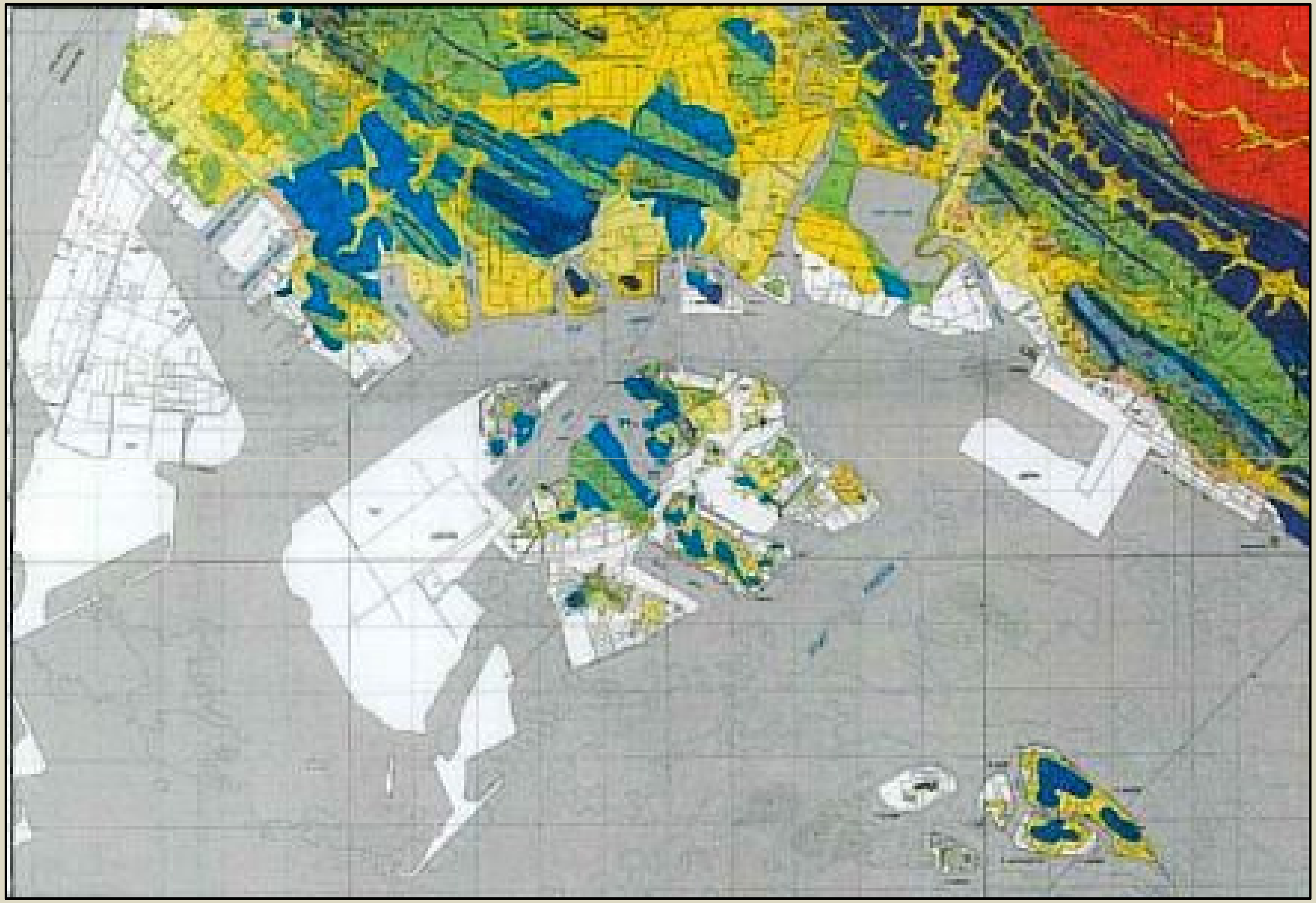
In common usage, ***liquefaction refers to the loss of strength in saturated, cohesion-less soils due to the build-up of pore water pressures during dynamic loading***.

GEOTECTNICAL ASPECT



Reclaimed areas in the east of Singapore (white).

GEOTECTNICAL ASPECT



Reclaimed areas in south west of Singapore (white)

Sladen et al. (1985) defined liquefaction as:

"Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic, or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance"

Liquefaction Assessment

Evaluating the **liquefaction resistance** of soils is an important step in the engineering design of new structures and the retrofit of existing structures in **earthquake-prone regions**.

The evaluation procedure widely used throughout the world is termed the simplified procedure.

This simplified procedure was originally developed by Seed and Idriss (1971) using blow counts from the Standard Penetration Test (SPT) correlated with a parameter representing the seismic loading on the soil, called the **Cyclic Stress Ratio (CSR)**.

This parameter is compared to Cyclic Resistance Ratio (CRR) of the soil and if it exceeds CRR, the soil is likely to be liquefied. A safety factor against liquefaction is defined as ratio of CRR to CSR:

*Safety Factor = CRR / CSR * Kσ * Kα*
*CRR = CRR1ave * MSF*

Where:

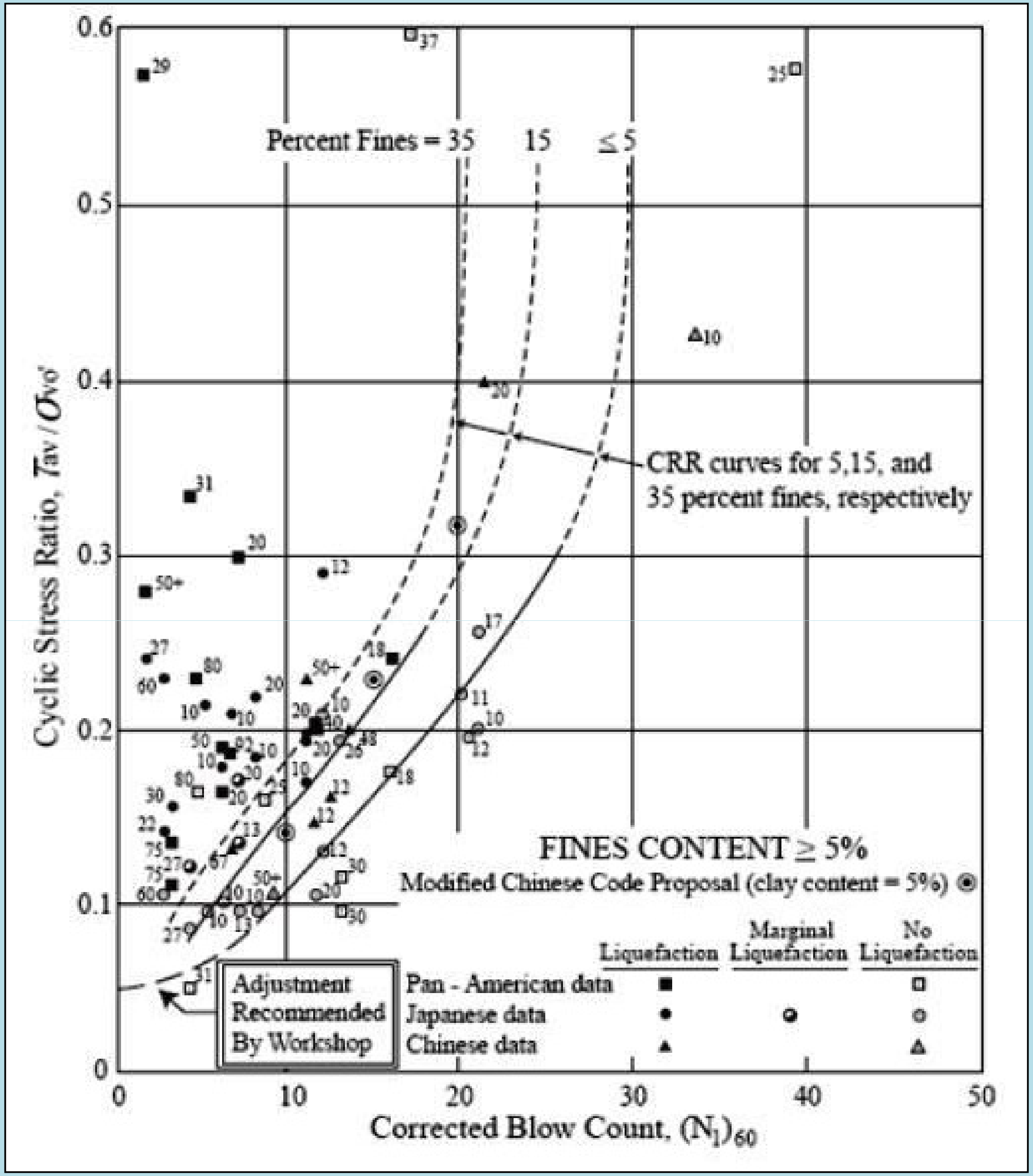
CRR1ave : calculated **cyclic resistance ratio** (average of all selected methods at a desired depth)

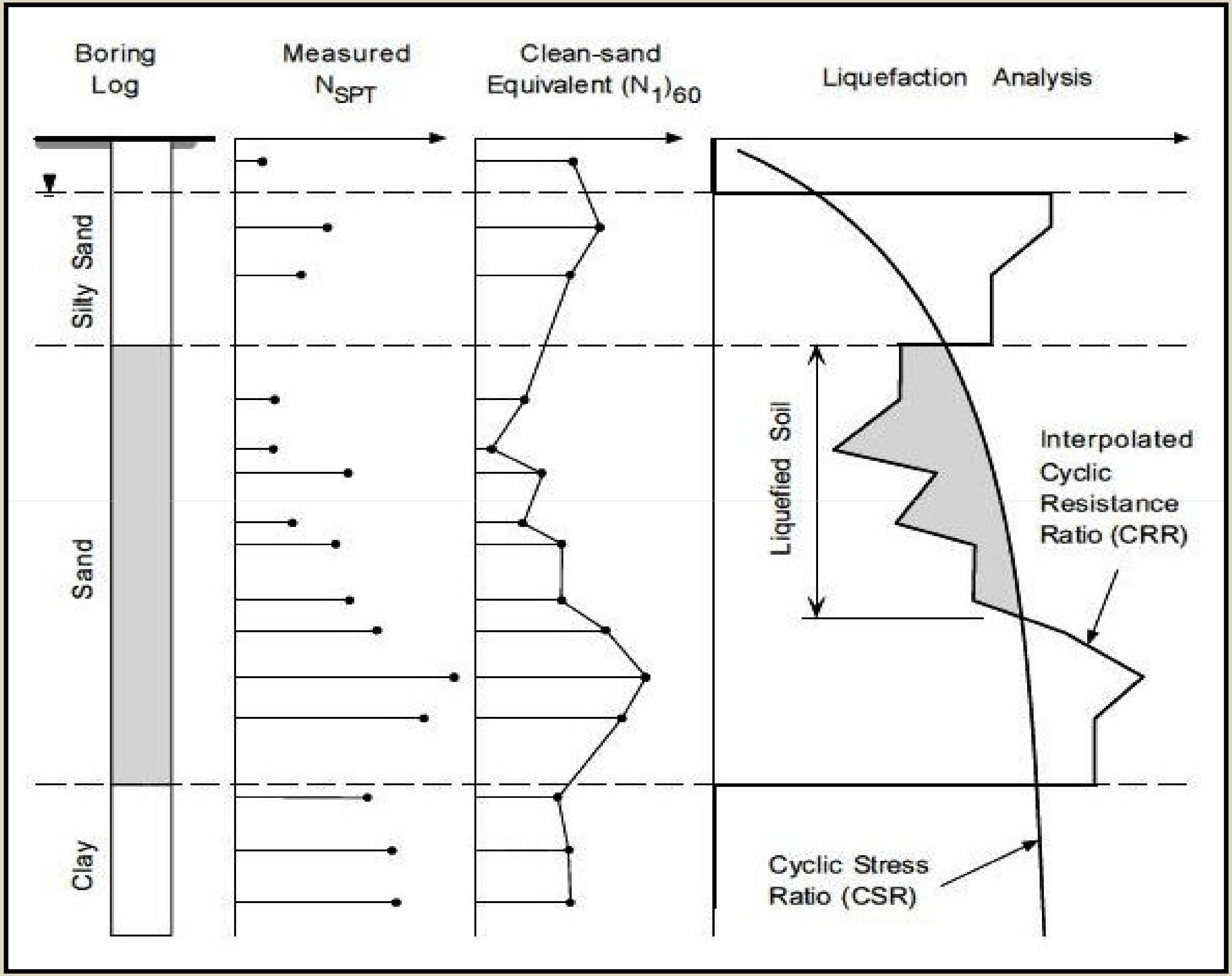
MSF : Magnitude Scaling Factor
Kσ : overburden stress correction factor; only applied to the following analysis methods:

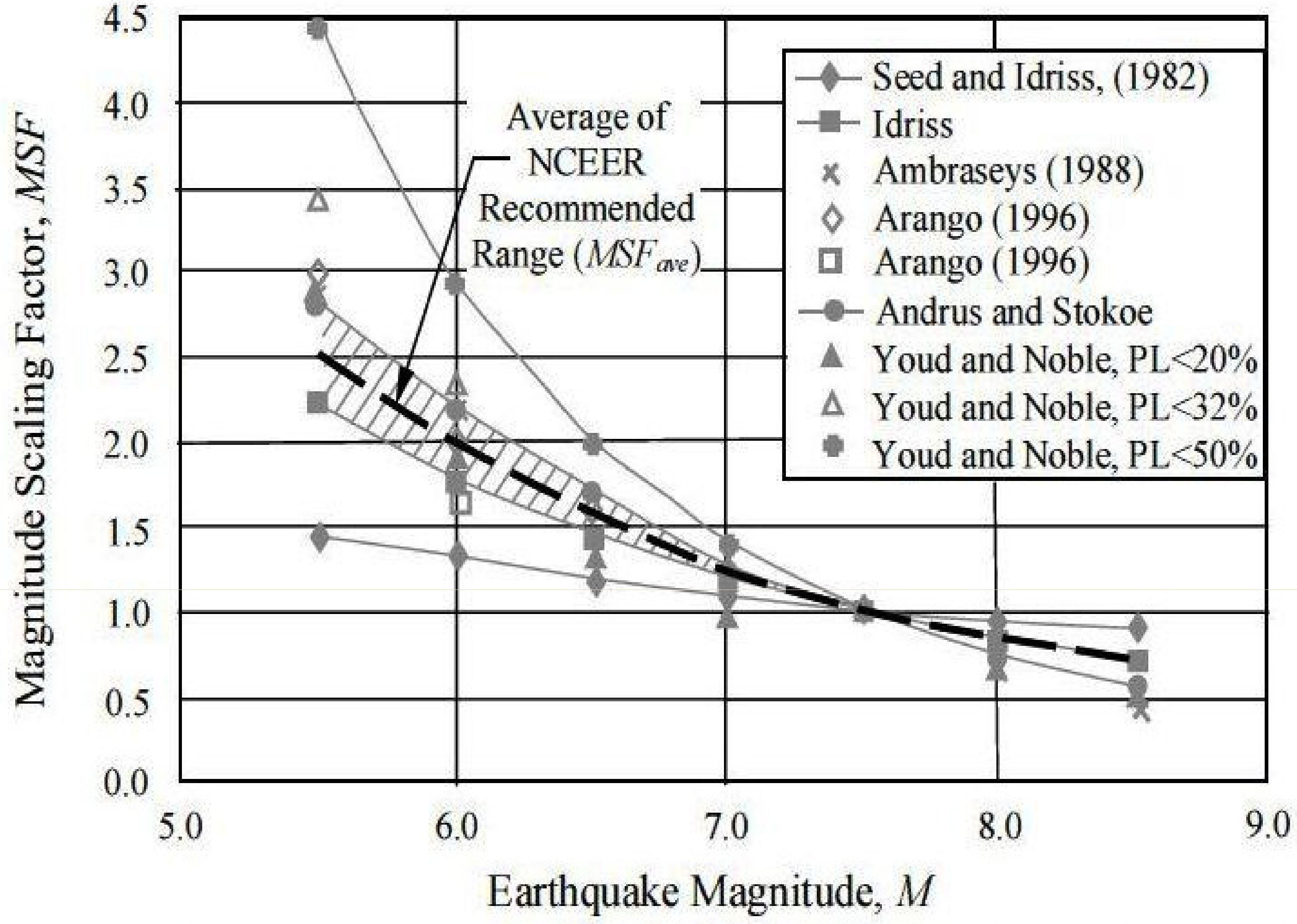
- Vancouver Task Force Report (2007)
- NCEER (1996)
- Cetin et al. (2004)
- Idriss & Boulanger (2004)

(each of the above-mentioned methods has its own equation for calculating Kσ , overburden stress correction factor and
Kα : ground slope correction)

Cyclic Stress Ratio,
Corrected SPT
& Fines Content

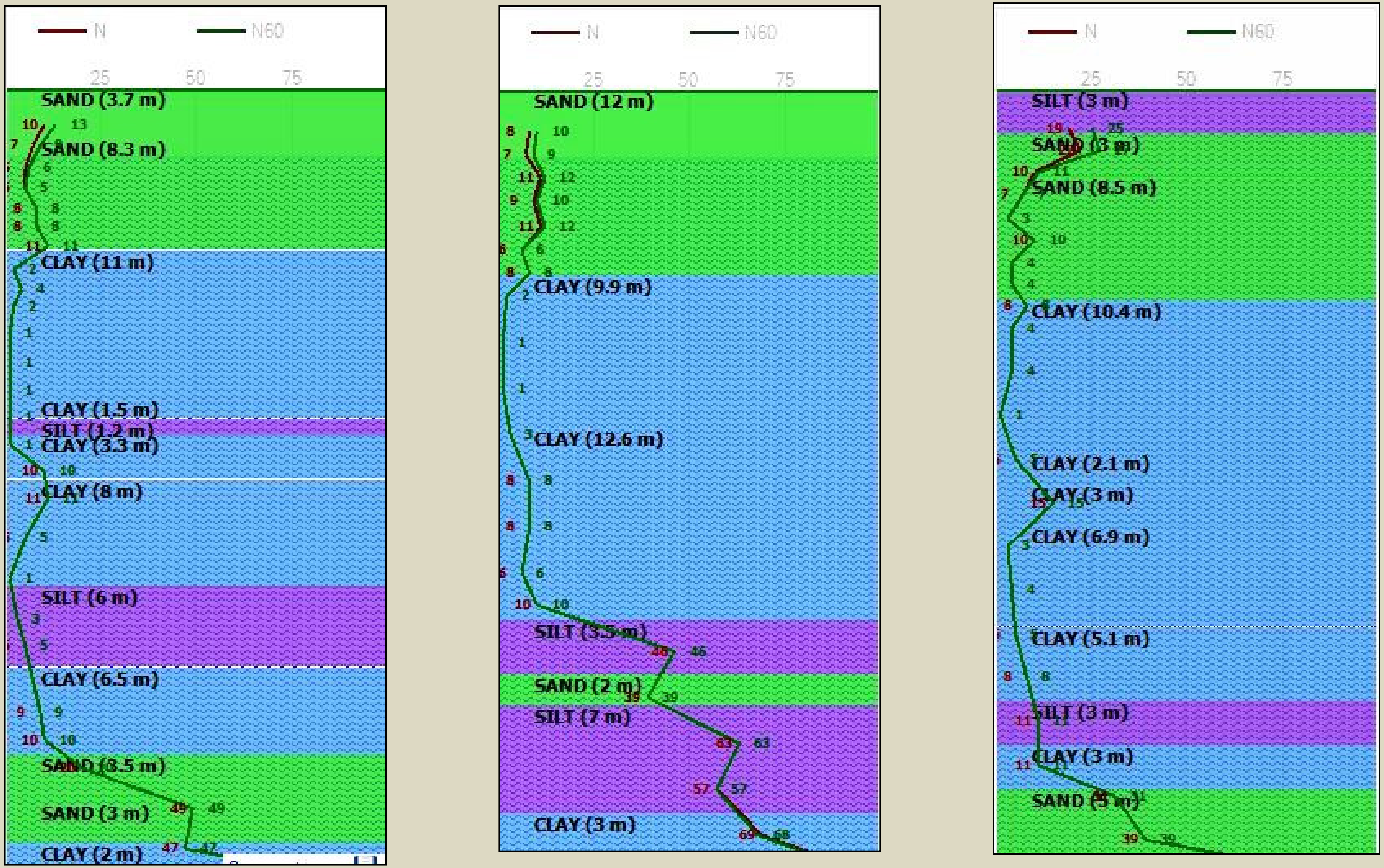



Boring Log
Measured N_{SPT}
Clean-sand Equivalent $(N_1)_{60}$
Liquefaction Analysis
Silty Sand
Sand
Clay
Liquefied Soil
Interpolated Cyclic Resistance Ratio (CRR)
Cyclic Stress Ratio (CSR)



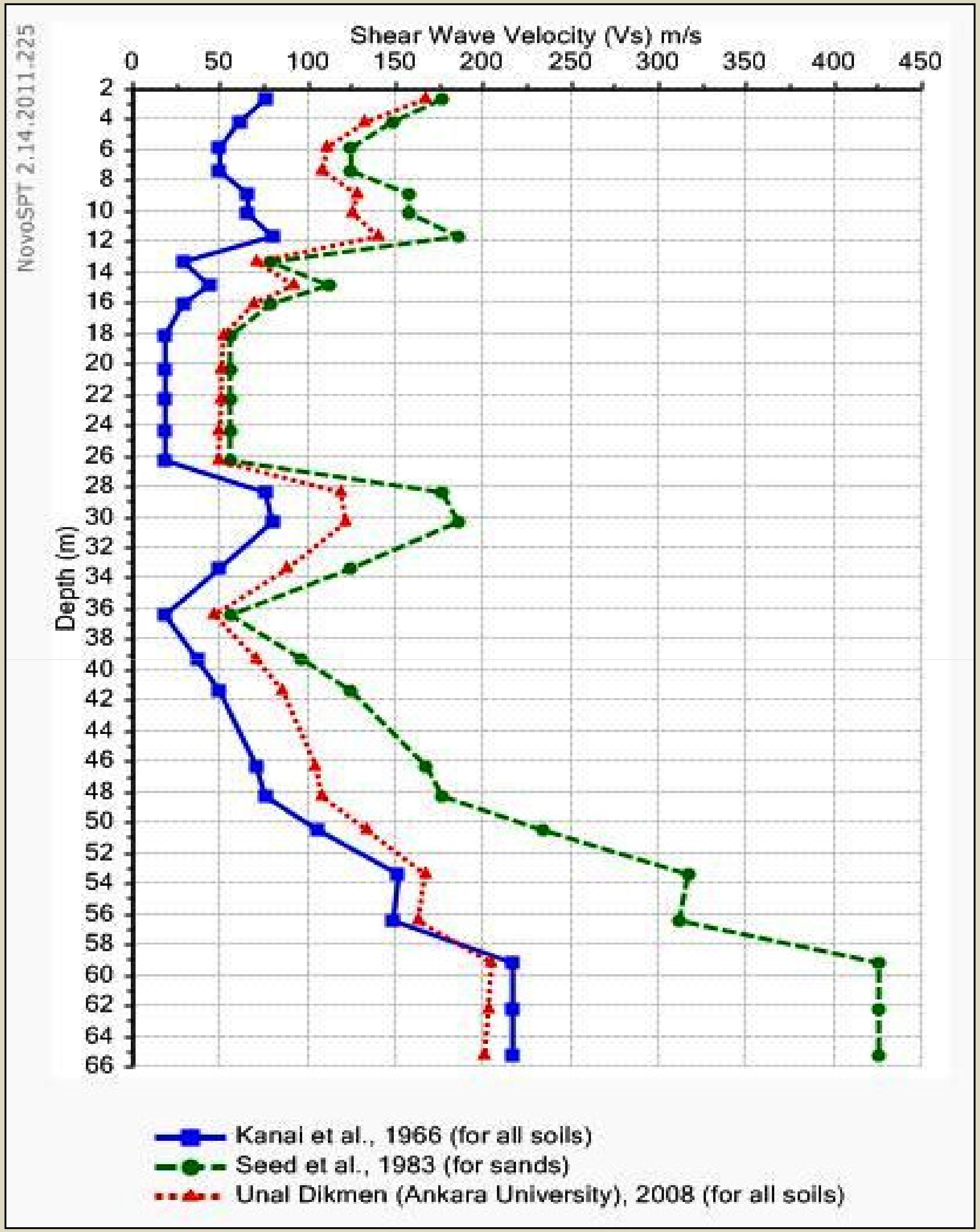
Magnitude scaling factors proposed by various investigators. (Adapted from Youd and Noble 1997).

Magnitude scaling factor for Earthquake Magnitude.



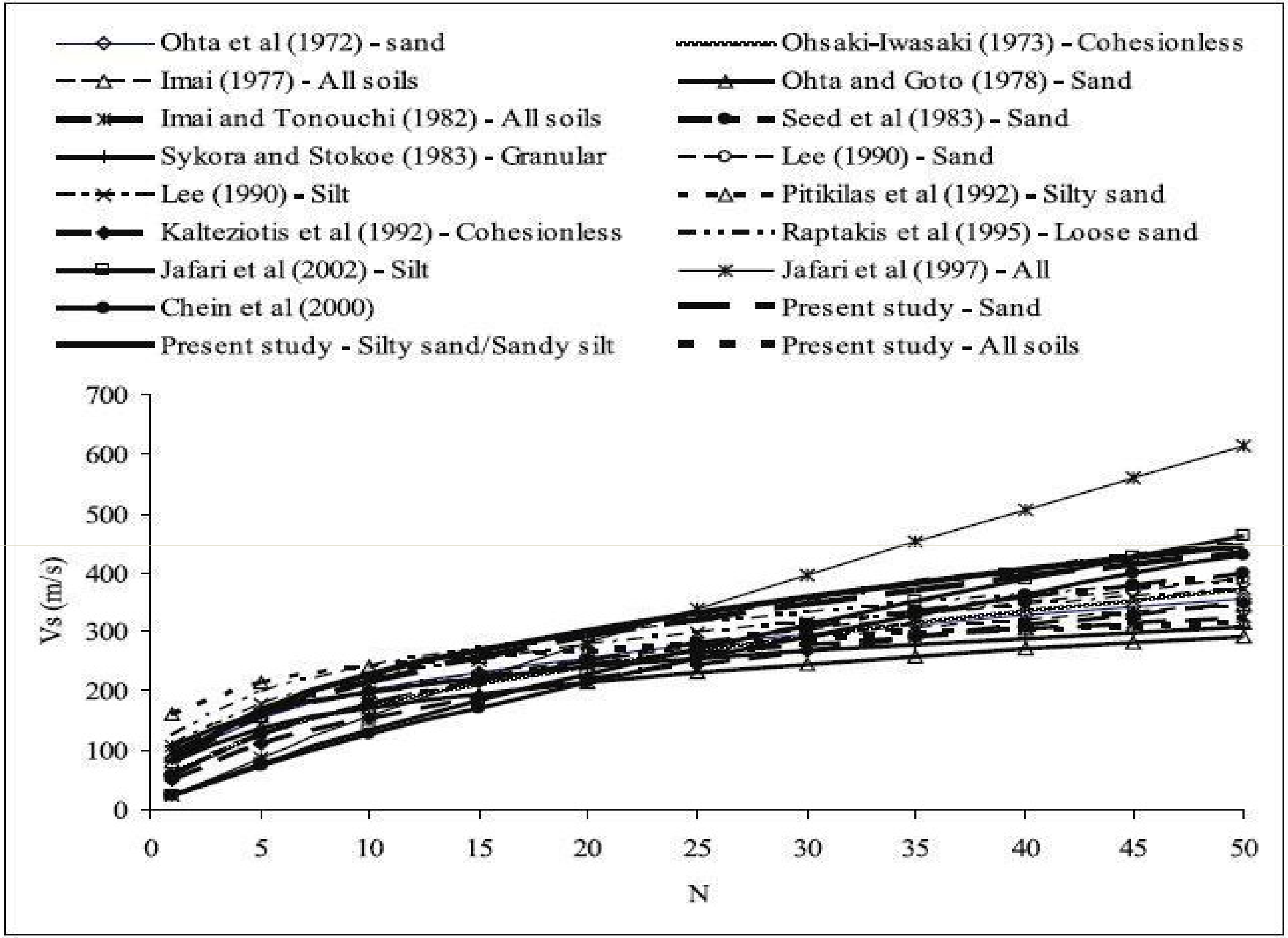
Generalized soil profiles in a reclaimed area south of Singapore.

Shear wave velocity
of
soils in Reclaimed area in
south of Singapore.



Depth (m)	SPT N	SPT N60=N.Ce.Cs.Cr .Cb	Lithology	GSD	Vs, m/s
2.65	13	10	Sand	7:88:5:0	150 - 194 (Schmertmann, 1978; Seed & Idriss, 1981)
4.15	9	7			
5.85	6	5			
7.35	5	5			120 - 174 (Schmertmann, 1978; Seed & Idriss, 1981)
8.85	8	8			
10.15	8	8			
11.65	11	11			
13.35	2	2	Clay & Silt		90 - 123 (Kiku, 2001; Seed & Idriss)
14.85	4	4			
16.15	2	2			
18.15	1	1			
20.35	1	1			
22.35	1	1			
24.35	1	1			
26.35	1	1			
28.35	10	10			
30.35	11	11			
33.35	5	5			
36.35	1	1			
39.35	3	3			
41.35	5	5			
46.35	9	9			

A detailed description of soil profile in reclaimed area showing GSD and calculated Vs.



C H Rao and G V Ramana (2008): Dynamic Soil Properties for Microzonation of Dehli, India. Journal of Earth Syst. Sci. 117, S2, pp. 719-730.

Site Classification for Seismic Site Response

Site Class	*Soil* Profile Name	Average Properties in Top 30 m as per Appendix A		
		Soil Shear Wave Average Velocity, V_s (m/s)	Standard Penetration Resistance, N_{60}	*Soil* Undrained Shear Strength, s_u
A	Hard *Rock*	$V_s > 1500$	Not applicable	Not applicable
B	*Rock*	$760 < V_s \, 1500$	Not applicable	Not applicable
C	Very Dense *Soil* and Soft *Rock*	$360 < V_s < 760$	$N_{60} > 50$	$s_u > 100$ kPa
D	Stiff *Soil*	$180 < V_s < 360$	$15 < N_{60} < 50$	$50 < s_u < 100$kPa
E	Soft *Soil*	$V_s < 180$	$N_{60} < 15$	$s_u < 50$kPa
E		Any profile with more than 3 m of *soil* with the following characteristics: • Plastic index PI > 20 • Moisture content w >= 40%, and • Undrained shear strength s_u < 25 kPa		
F	(1) Others	Site Specific Evaluation Required		

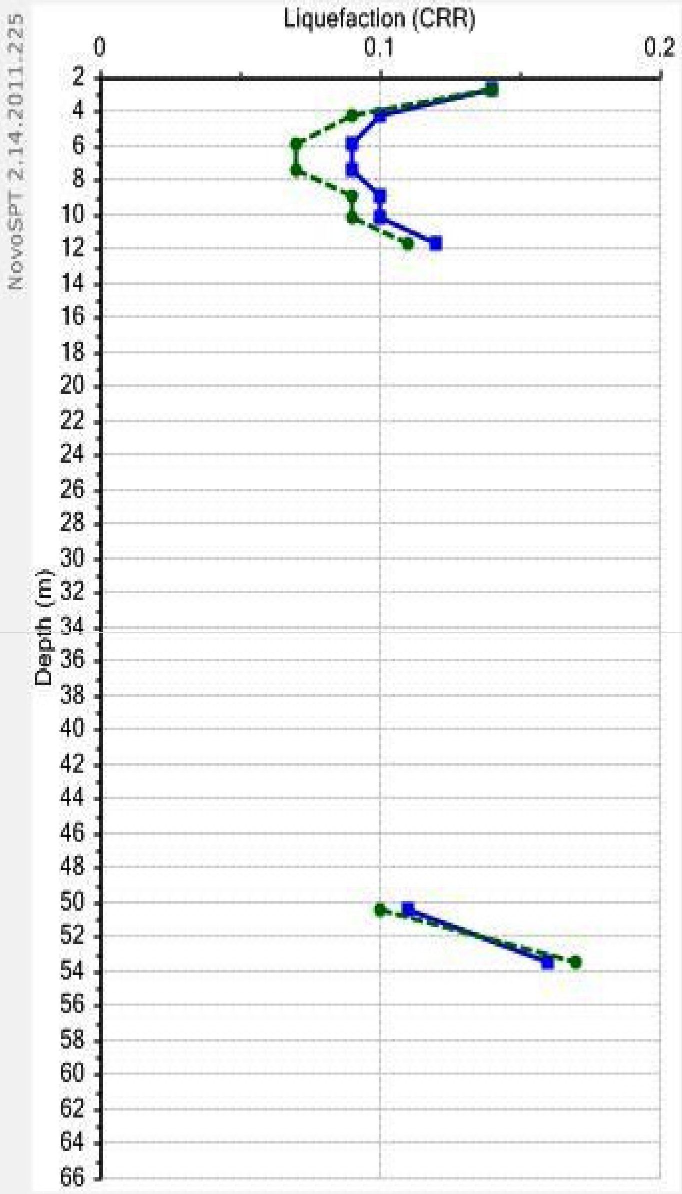
(1) Other *soils* include:
a) Liquefiable *soils*, quick and highly sensitive clays, collapsible weakly cemented *soils*, and other *soils* susceptible to failure or collapse under seismic loading.
b) Peat and/or highly organic clays greater than 3 m in thickness.
c) Highly plastic clays (PI > 75) with thickness greater than 8 m.
d) Soft to medium stiff clays with thickness greater than 30 m.

Site Classification for Seismic Site Response (Hunter et al., 2006)

Geotechnical site categories proposed by Rodriguez-Marek et al. (2001)

Site	Description	Site Period	Comments
A	Hard Rock	< 0.1 s	Hard, strong, intact rock; V_s > 1500 m/s
B	Rock	< 0.2 s	Most "unweathered" California rock cases (V_s > 760 m/s or < 6 m of soil)
C-1	Weathered/Soft Rock	< 0.4 s	Weathered zone > 6 m and < 30 m (V_s > 360 m/s increasing to 700 m/s).
C-2	Shallow Stiff Soil	< 0.5 s	Soil depth > 6 m and < 30 m
C-3	Intermediate Depth Stiff Soil	< 0.8 s	Soil depth > 30 m and < 60 m
D-1	Deep Stiff Holocene Soil, either S (Sand) or C (Clay)	< 1.4 s	Soil depth > 60 m and < 200 m. Sand has low fines content (< 15%) or nonplastic fines (PI < 5). Clay has high fines content (> 15%) and plastic fines (PI > 5).
D-2	Deep Stiff Pleistocene Soil, S (Sand) or C (Clay)	< 1.4 s	Soil depth > 60 m and < 200 m. See D-1 for S or C sub-categorization.
D-3	Very Deep Stiff Soil	< 2 s	Soil depth > 200 m
E-1	Medium Depth Soft Clay	< 0.7 s	Thickness of soft clay layer 3 m to 12 m
E-2	Deep Soft Clay Layer	< 1.4 s	Thickness of soft clay layer > 12 m
F	Special, e.g., Potentially Liquefiable Sand or Peat	= 1 s	Holocene loose sand with high water table (z_w < 6 m) or organic peat.

Cyclic Resistance Ratio (CRR) of sand layer in reclaimed area of southern Singapore.



Data

Depth (m)	Idriss and Boulanger, 2004	NCEER 1997 Workshop Report
2.65	0.14	0.14
4.15	0.1	0.09
5.85	0.09	0.07
7.35	0.09	0.07
8.85	0.1	0.09
10.15	0.1	0.09
11.65	0.12	0.11
13.35		
14.85		
16.15		
18.15		
20.35		
22.35		
24.35		
26.35		
28.35		
30.35		
33.35		
36.35		
39.35		
41.35		
46.35		
48.35		
50.45	0.11	0.1
53.45	0.16	0.17
56.45		
59.26		
62.28		

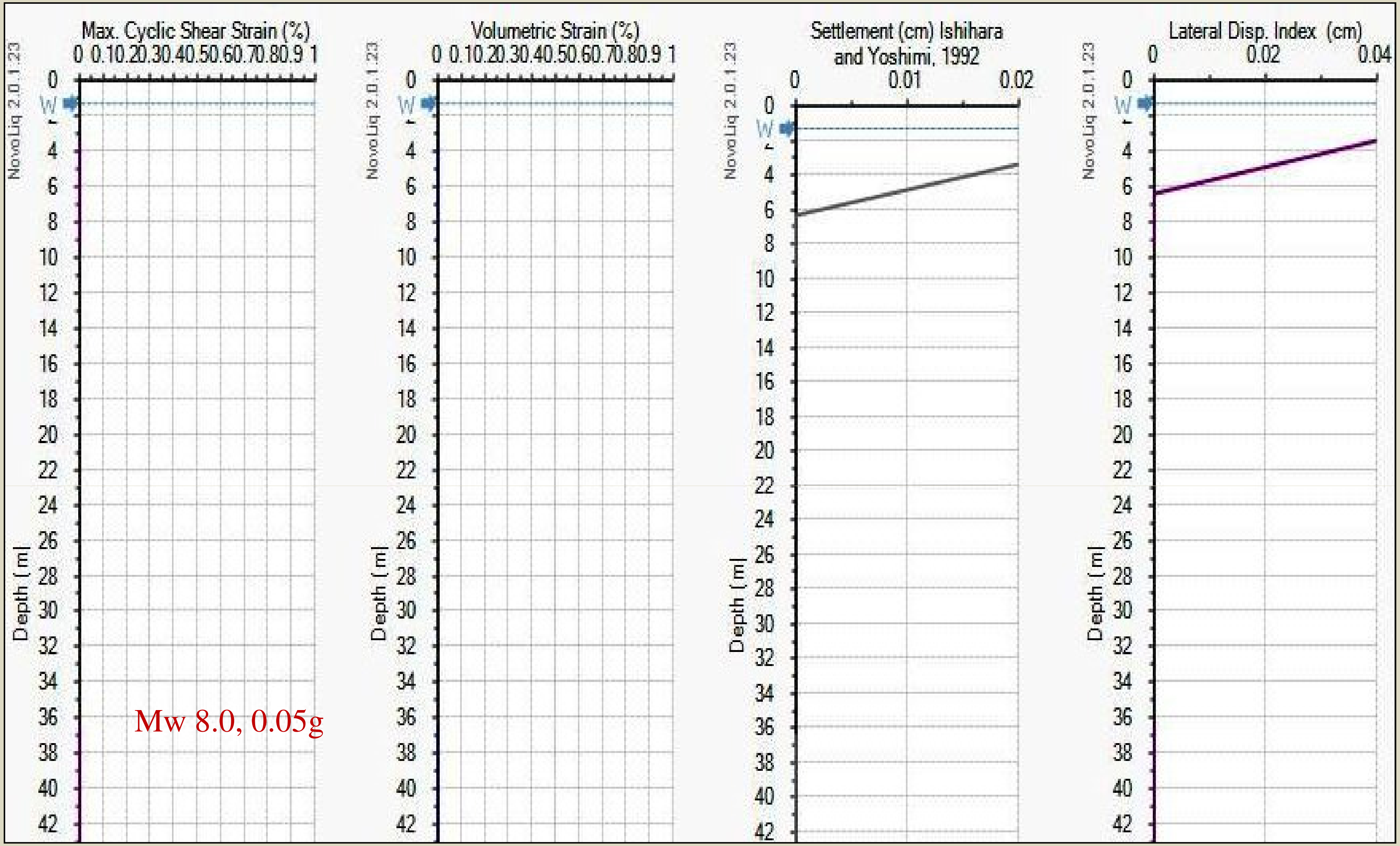
Liquefaction Trigerring | Post-Liquefaction Parameters | Ksigma

Mw 8.0, 0.05g

Table II : Details of lateral spreading, vertical settlement and residual settlement calculations

Depth (m)	Max. Cyclic Shear Strain (%)	Volumetric Strain (%)	Lateral Spreading		Settlement (cm)		Residual Strength Sr (kPa)	
			delta LDI	LDI	delta S	S	Lower limit	Upper limit
2.65	-	-	-	-	-	-	-	-
3.45	0	0	0.04	0.04	0.02	0.02	2.9	33.3
6.45	0	0	0	0	0	0	9.1	44.5
9.45	0	0	0	0	0	0	9.6	61.1
12.45	-	-	-	-	-	-	-	-
20.5	-	-	-	-	-	-	-	-
27.45	-	-	-	-	-	-	-	-
36.45	0	0	0	0	0	0	59.7	194.8
39.45	0	0	0	0	0	0	78	217
42.29	0	0	0	0	0	0	233.3	238.1
45.4	0	0	0	0	0	0	255.9	261.2
48.3	0	0	0	0	0	0	277	282.7
51.29	0	0	0	0	0	0	298.7	304.8
55.1	0	0	0	0	0	0	326.4	333.1
57.1	0	0	0	0	0	0	341	347.9

Post-liquefaction parameters for a Mw 8.0 and 0.05g for reclaimed area in south of Singapore.



Very low Settlement and Lateral Displacement values for Mw 8.0 and 0.05g.

Liquefaction Trigerring | Post-Liquefaction Parameters | Ksigma

Mw 8.5, 0.05g

Table II : Details of lateral spreading, vertical settlement and residual settlement calculations

Depth (m)	Max. Cyclic Shear Strain (%)	Volumetric Strain (%)	Lateral Spreading		Settlement (cm)		Residual Strength Sr (kPa)	
			delta LDI	LDI	delta S	S	Lower limit	Upper limit
2.65	-	-	-	-	-	-	-	-
3.45	0	0	0.06	0.06	0.04	0.04	2.9	33.3
6.45	0	0	0	0	0	0	9.1	44.5
9.45	0	0	0	0	0	0	9.6	61.1
12.45	-	-	-	-	-	-	-	-
20.5	-	-	-	-	-	-	-	-
27.45	-	-	-	-	-	-	-	-
36.45	0	0	0	0	0	0	59.7	194.8
39.45	0	0	0	0	0	0	78	217
42.29	0	0	0	0	0	0	233.3	238.1
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48.3	0	0	0	0	0	0	277	282.7
51.29	0	0	0	0	0	0	298.7	304.8
55.1	0	0	0	0	0	0	326.4	333.1
57.1	0	0	0	0	0	0	341	347.9

Post-liquefaction parameters calculated for Mw 8.5 and 0.05g.

Liquefaction Trigerring | Post-Liquefaction Parameters | Ksigma

Table I : Details of liquefaction triggering analysis for all selected methods

Depth (m)	Rd	Overburden Pressure		Fines Content (%)	SPT Test				Relative Density Dr (%)	Cyclic Stress Ratio	Cyclic Resistance Ratio			Average CRR	Safety Factor
		Total	Effective		N60	Co	Cn	N1(60)cs			Vancouv	Boulang	Cetin et		
2.65	0.982	54.33	54.33	0	18	0.75	1.22	17	59.9	0.032	-	-	-	-	-
4.15	0.972	78.4	78.4	8	9	0.79	0.98	7	40.1	0.032	-	-	-	-	-
5.85	0.959	103.39	87.21	8	11	0.9	0.96	10	46.5	0.037	0.11	0.12	0.05	0.14	3.73
7.35	0.945	125.44	94.55	8	10	0.93	0.94	9	44.6	0.041	0.1	0.11	0.05	0.13	3.17
8.85	0.925	147.49	101.89	8	8	0.96	0.93	7	40.4	0.044	0.08	0.1	0.04	0.11	2.63
10.35	0.898	169.55	109.23	8	6	0.97	0.91	6	35.1	0.045	0.07	0.09	0.05	0.1	2.26
11.85	0.861	191.6	116.57	8	2	0.98	0.9	2	21.2	0.046	0.05	0.07	0.05	0.08	1.8
13.35	0.816	217.7	127.96	4	10	0.98	0.87	9	43.2	0.045	0.09	0.11	0.05	0.12	2.73
14.85	0.766	244.25	139.8	4	12	0.99	0.85	10	46.9	0.043	0.11	0.12	0.04	0.14	3.11
16.35	0.716	270.8	151.64	4	12	0.99	0.83	10	46.3	0.042	0.11	0.11	0.04	0.13	3.18
18.35	0.658	306.2	167.43	4	13	1	0.8	10	47.5	0.039	0.11	0.12	0.04	0.14	3.47
23.35	0.561	398.95	211.15	0	4	1	0.73	3	25.3	0.034	-	-	-	-	-
35.35	0.474	614.27	308.79	0	15	1.01	0.62	9	45	0.031	-	-	-	-	-
37.45	0.465	648.92	322.84	0	12	1.01	0.6	7	39.8	0.03	-	-	-	-	-
40.45	0.454	698.42	342.92	0	17	1.01	0.59	10	46.7	0.03	-	-	-	-	-
43.45	0.444	753	368.08	0	77	1.01	0.56	44	97.5	0.029	-	-	-	-	-
46.38	0.434	811.6	397.94	0	100	1.01	0.54	54	100	0.029	-	-	-	-	-
49.43	0.425	872.6	429.03	0	100	1.01	0.52	52	100	0.028	-	-	-	-	-
52.33	0.417	930.6	458.59	0	100	1.01	0.5	50	100	0.027	-	-	-	-	-

Mw 7.5, 0.05g

Safety Factor = CRR / CSR   CRR = CRR1.MSF.K   Cn : depth correction factor   N60 = N.Cr.Ce.Cb.Cs   N1(60) = N60.Cn and corrected for fines content

Cyclic Stress Ratio, Cyclic Resistance Ratio and Safety Factor for Mw 7.5 and 0.05g.

Liquefaction Trigerring | Post-Liquefaction Parameters | Ksigma

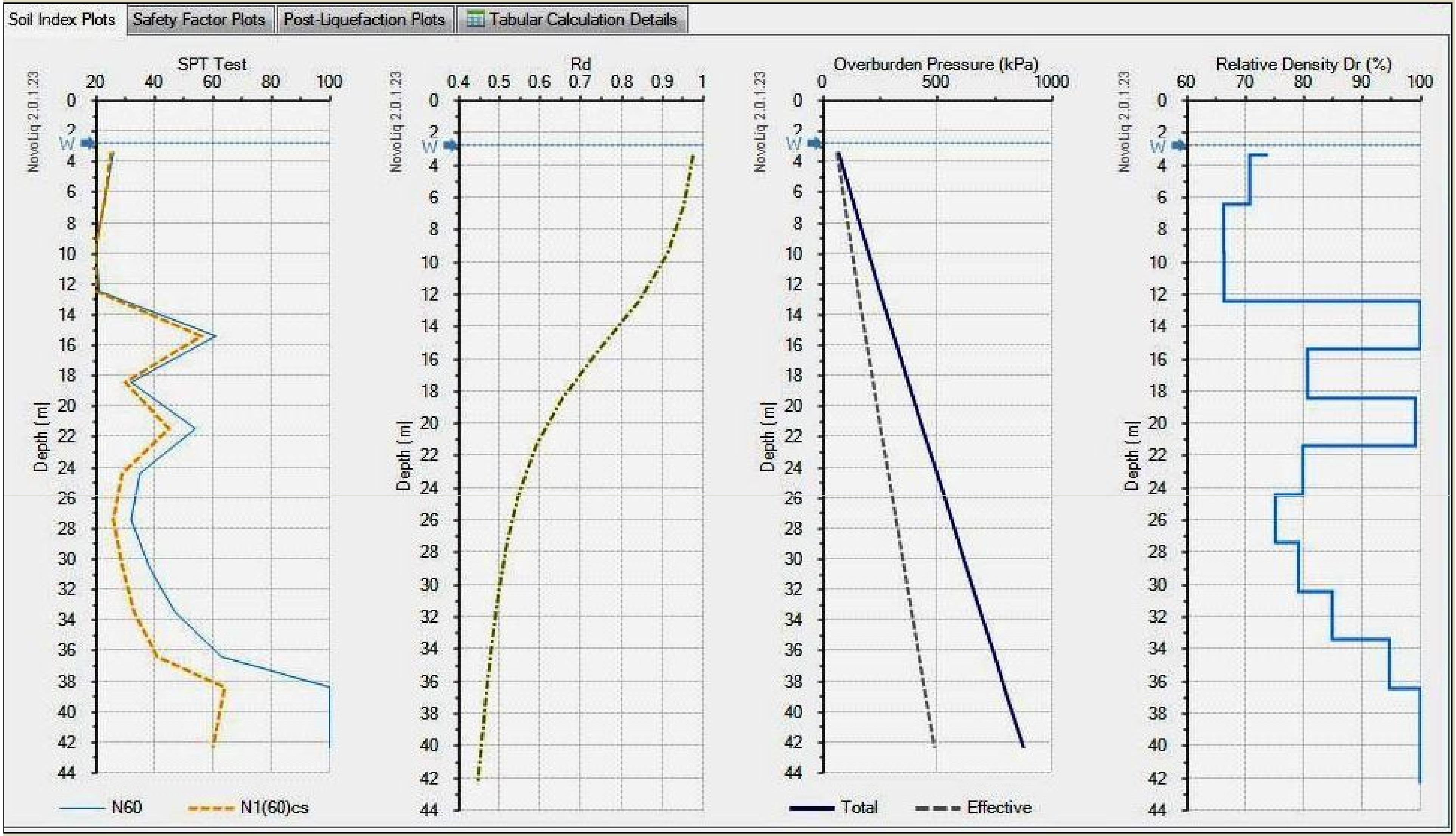
Table I : Details of liquefaction triggering analysis for all selected methods

Depth (m)	Rd	Overburden Pressure		Fines Content (%)	SPT Test				Relative Density	Cyclic Stress Ratio	Cyclic Resistance Ratio (CRR1)				Average CRR	Safety Factor
		Total	Effective		N60	Co	Cn	N1(60)cs	Dr (%)		Vancouv	NCEER	Boulang	Cetin et		
2.65	0.982	54.33	41.58	0	18	0.75	1.46	20	65.5	0.042	-	-	-	-	-	-
3.45	0.976	68.11	47.52	8	5	0.75	1.34	5	34.2	0.045	0.07	0.07	0.09	0.05	0.08	**1.78**
6.45	0.954	113.56	63.55	44	10	0.9	1.09	17	60.5	0.055	0.18	0.18	0.18	0.1	0.19	**3.4**
9.45	0.915	166.66	87.23	40	7	0.96	0.96	13	52.6	0.057	0.14	0.14	0.14	0.06	0.14	**2.48**
12.45	0.843	219.76	110.91	0	10	0.98	0.91	9	44	0.054	-	-	-	-	-	-
20.5	0.608	350.85	163.05	0	1	1	0.81	1	13.2	0.042	-	-	-	-	-	-
27.45	0.519	461.86	205.9	0	14	1	0.74	10	47.6	0.038	-	-	-	-	-	-
36.45	0.469	622.38	278.15	30	24	1.01	0.65	23	70.5	0.034	0.25	0.2	0.23	0.09	0.23	**6.75**
39.45	0.458	683.58	309.93	30	28	1.01	0.62	25	73.4	0.033	0.28	0.22	0.27	1	0.52	**15.95**
42.29	0.448	741.52	340.02	30	100	1.01	0.59	73	100	0.032	0.8	0.61	0.75	1	0.94	**29.5**
45.4	0.437	804.96	372.96	30	100	1.01	0.56	70	100	0.031	0.8	0.59	0.74	1	0.93	**30.32**
48.3	0.428	864.12	403.68	30	100	1.01	0.54	67	100	0.03	0.8	0.58	0.74	1	0.93	**31.05**
51.29	0.42	925.12	435.35	30	100	1.01	0.51	64	100	0.029	0.8	0.57	0.74	1	0.92	**31.78**
55.1	0.409	1002.84	475.71	30	100	1.01	0.49	61	100	0.028	0.8	0.55	0.73	1	0.92	**32.67**
57.1	0.404	1043.64	496.9	30	100	1.01	0.47	60	100	0.028	0.8	0.55	0.73	1	0.91	**33.13**

Mw 8.5, 0.05g

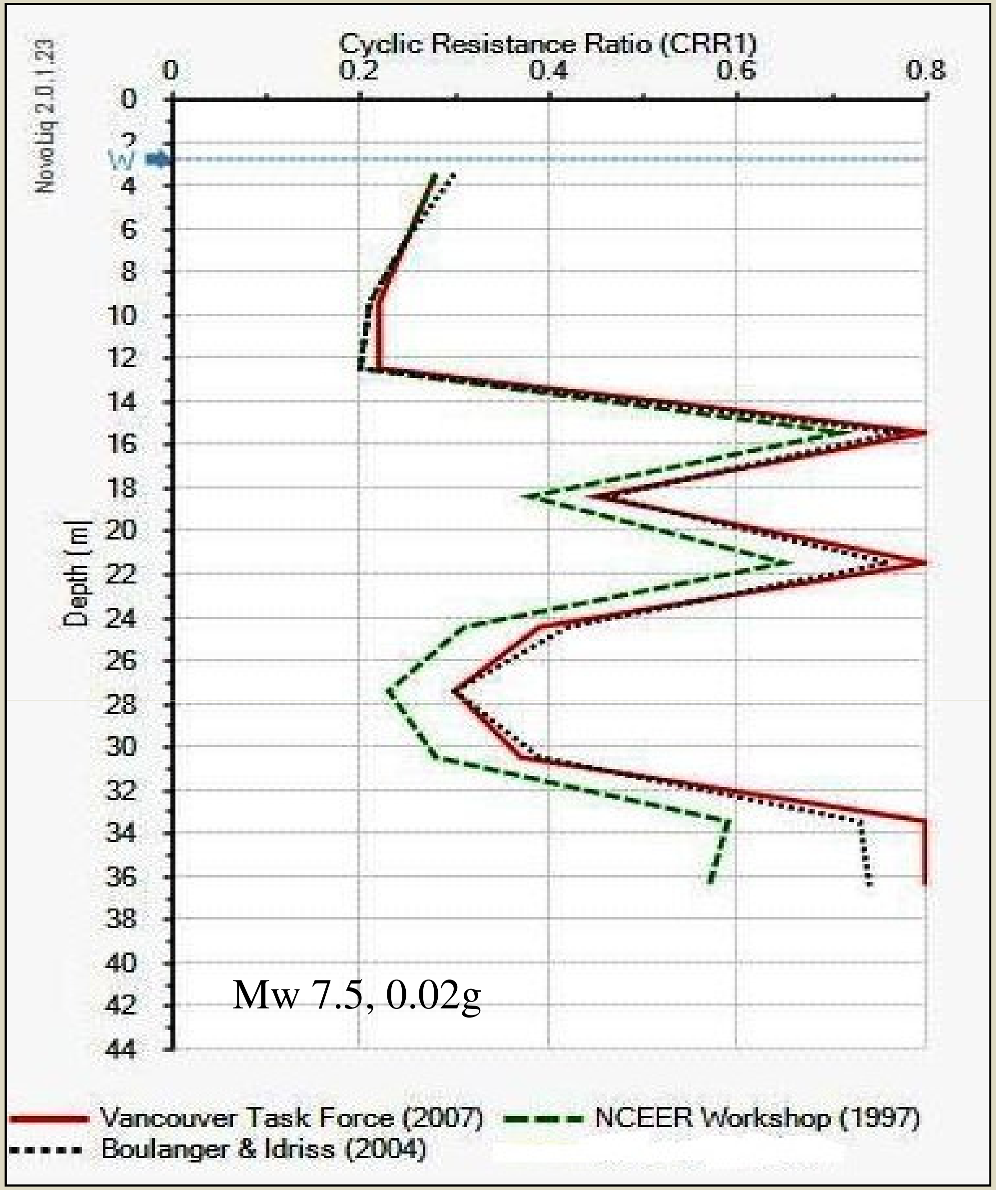
Safety Factor = CRR / CSR   CRR = CRR1.MSF.K   Cn : depth correction factor   N60 = N.Cr.Ce.Cb.Cs   N1(60) = N60.Cn and corrected for fines content

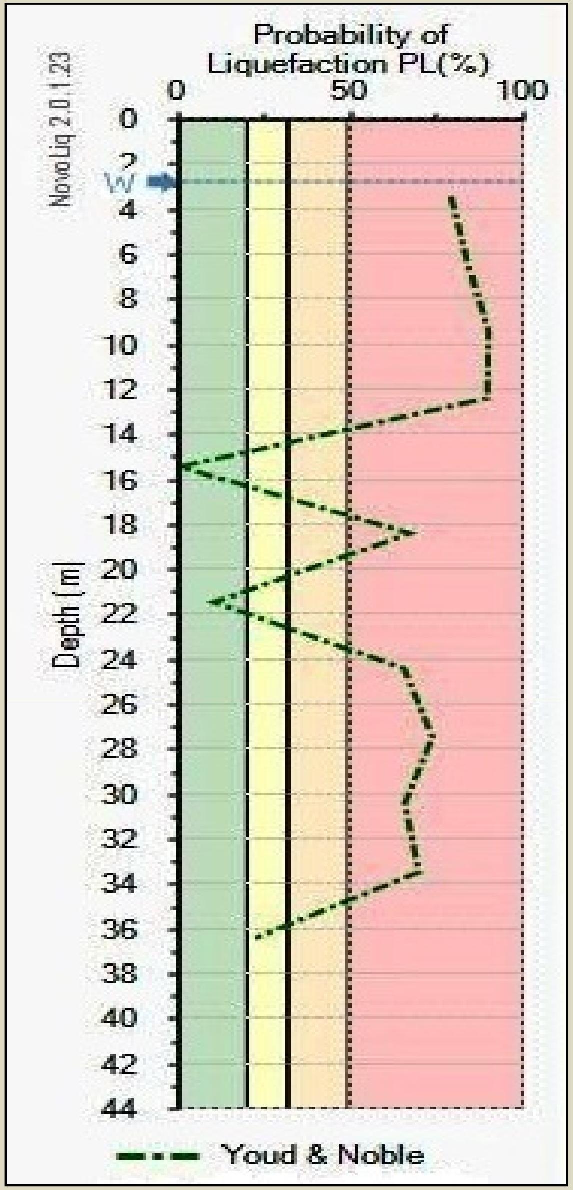
Cyclic Stress Ratio, Cyclic Resistance Ratio and Safety Factor for Mw 8.5 and 0.05g.



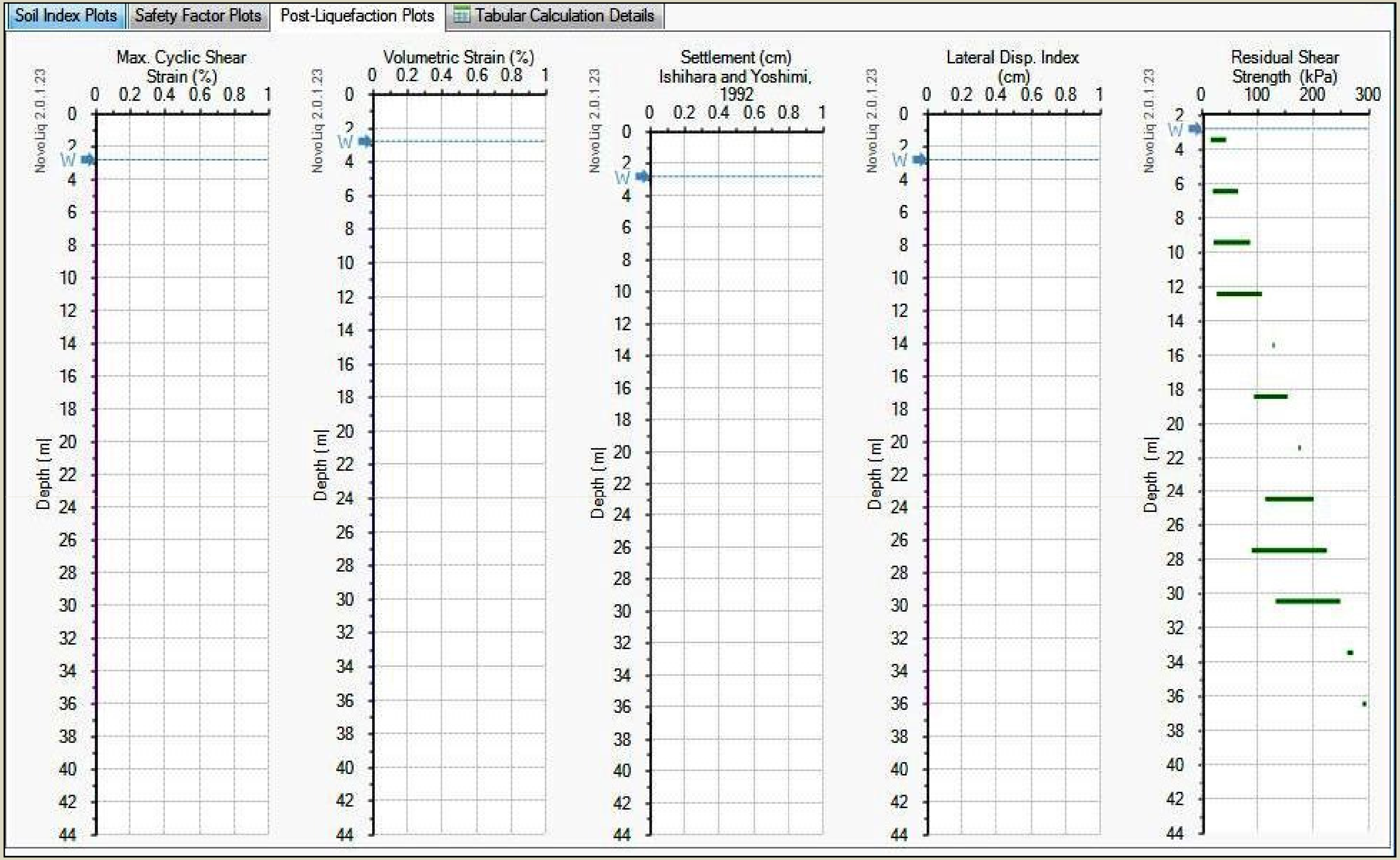
Soil Index plots of a reclaimed area in east of Singapore.

Rd: depth reduction factor

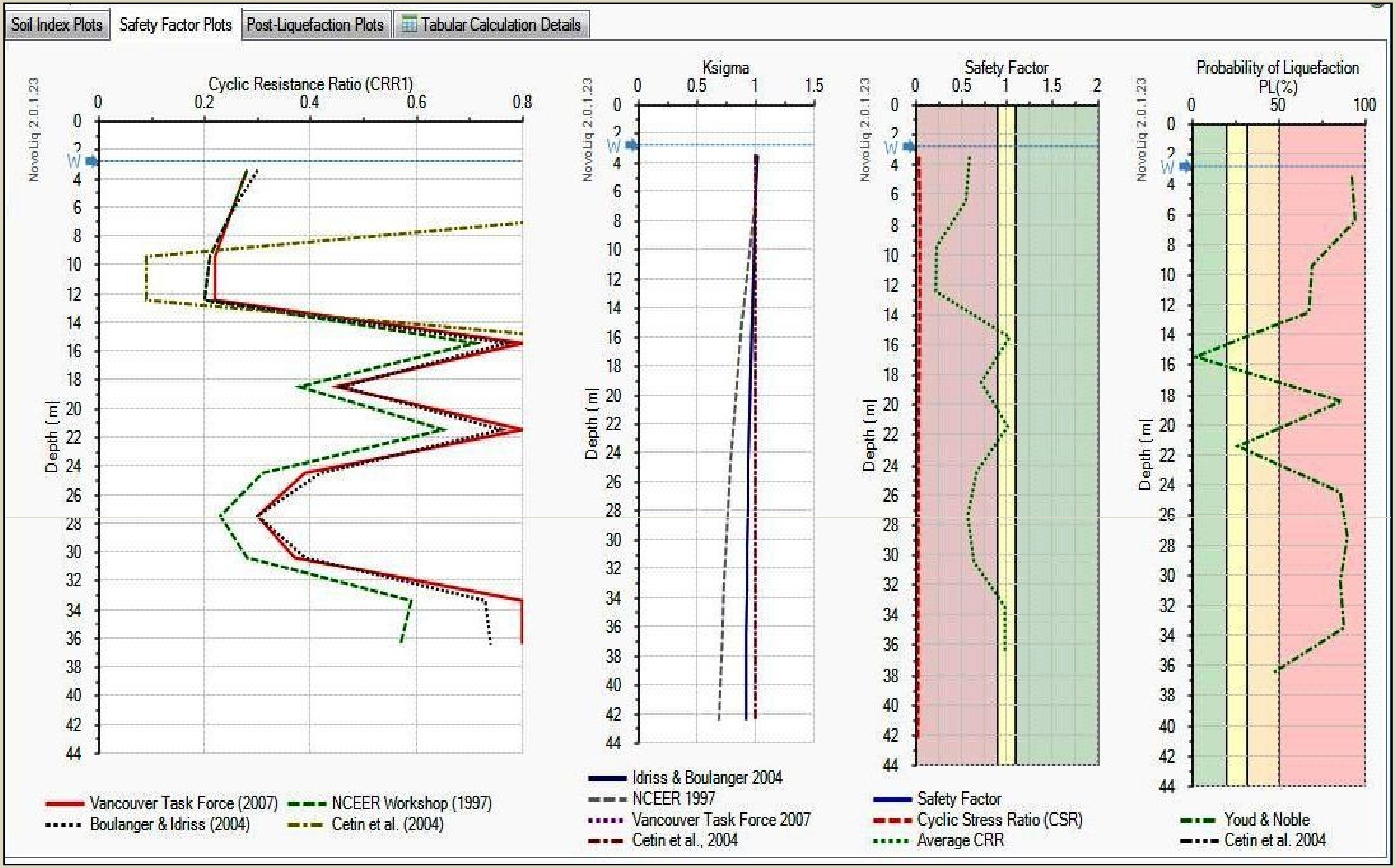




Magnitude Scaling factor (MSF): Seed & Idriss (1982), Depth reduction Factor (Thomas F Blake)



Post liquefaction plots for Mw: 7.5, PGA: 0.02g.



CRR, CSR and PL for Mw: 8.0, PGA: 0.05g (Magnitude Scaling factor (MSF): Seed & Idriss (1982), Depth reduction Factor by Thomas F Blake) (note:Ksigma=overburden stress correction factor)

Table I : Details of liquefaction triggering analysis for all selected methods

Depth (m)	Rd	Overburden Pressure		Fines Content (%)	SPT Test				Relative Density Dr (%)	Cyclic Stress Ratio	Cyclic Resistance Ratio (CRR1)				Average CRR	Safety Factor
		Total	Effective		N60	Co	Cn	N1(60)cs			Vancouv	NCEER	Boulang	Cetin et		
3.45	0.976	69	62.63	15	26	0.75	1.11	25	73.9	0.035	0.28	0.28	0.3	1	0.59	**16.77**
6.45	0.954	129	93.2	15	23	0.9	0.95	23	70.8	0.043	0.25	0.25	0.25	1	0.55	**12.87**
9.45	0.915	189	123.78	15	20	0.96	0.88	20	66.3	0.045	0.22	0.21	0.21	0.09	0.23	**5.02**
12.45	0.843	249	154.36	15	21	0.98	0.82	20	66.4	0.044	0.22	0.2	0.2	0.09	0.22	**5.05**
15.45	0.746	310.45	186.39	25	61	0.99	0.77	56	100	0.04	0.8	0.71	0.77	1	1.03	**25.5**
18.45	0.655	373.45	219.97	25	32	1	0.72	30	80.7	0.036	0.45	0.38	0.46	1	0.72	**19.84**
21.45	0.59	436.45	253.55	25	54	1	0.68	45	99.1	0.033	0.8	0.65	0.76	1	1.01	**30.58**
24.45	0.547	499.45	287.13	25	35	1	0.64	29	79.9	0.031	0.39	0.31	0.42	1	0.67	**21.52**
27.45	0.519	562.45	320.71	25	32	1	0.61	26	75.2	0.03	0.3	0.23	0.3	1	0.57	**19.38**
30.45	0.499	625.45	354.29	25	38	1.01	0.58	29	79.1	0.029	0.37	0.28	0.39	1	0.64	**22.31**
33.45	0.483	688.45	387.87	25	47	1.01	0.55	33	84.9	0.028	0.8	0.59	0.73	1	0.98	**35.08**
36.45	0.469	751.45	421.44	25	63	1.01	0.52	41	94.7	0.027	0.8	0.57	0.74	1	0.98	**35.9**
38.38	0.462	791.98	443.05	30	100	1.01	0.51	64	100	0.027	-	-	-	-	-	-
42.42	0.447	876.82	488.27	30	100	1.01	0.48	60	100	0.026	-	-	-	-	-	-

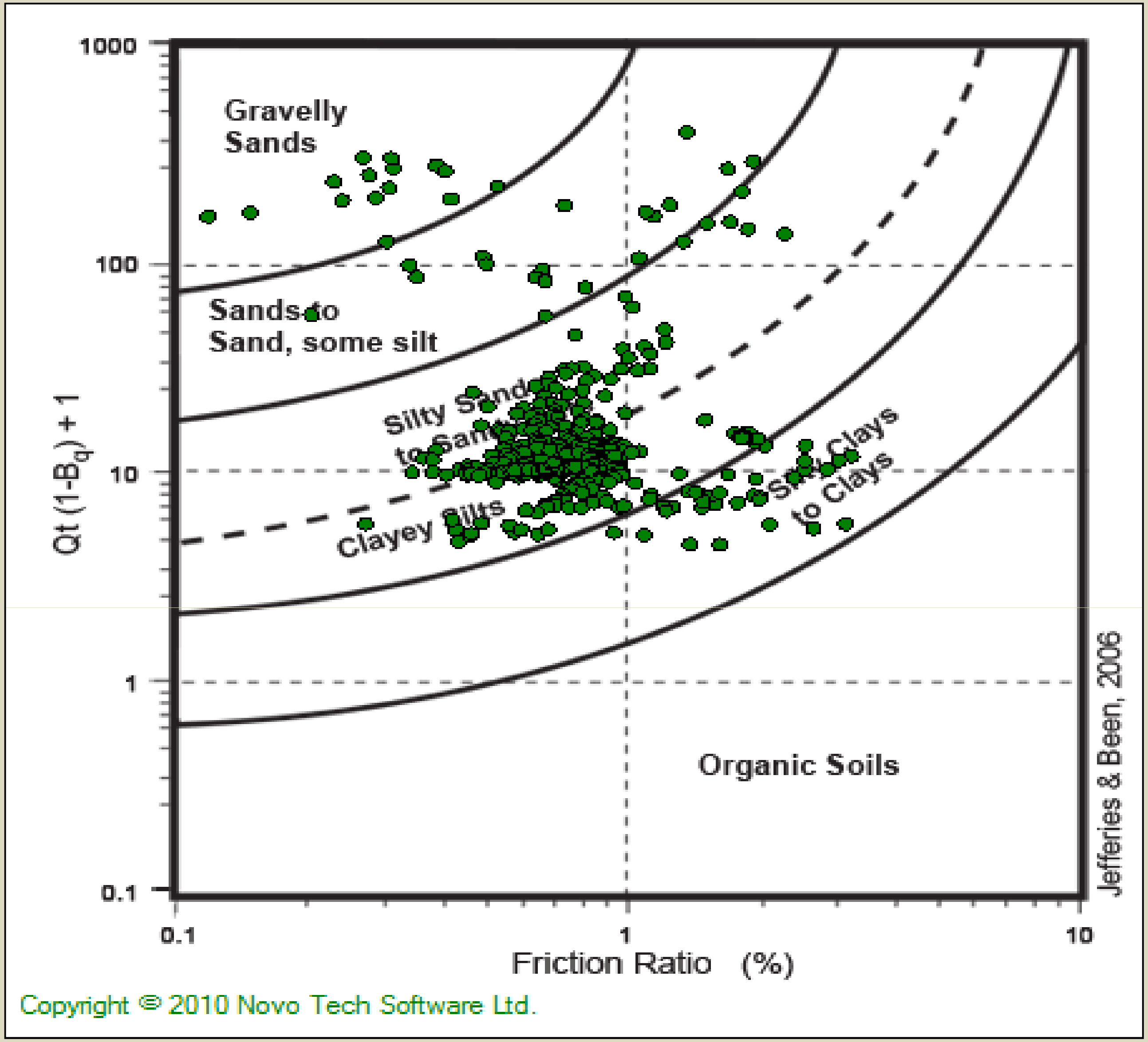
Mw: 8.0, PGA: 0.05g

Safety Factor = CRR / CSR   CRR = CRR1.MSF.K   Cn : depth correction factor   N60 = N.Cr.Ce.Cb.Cs   N1(60) = N60.Cn and corrected for fines content

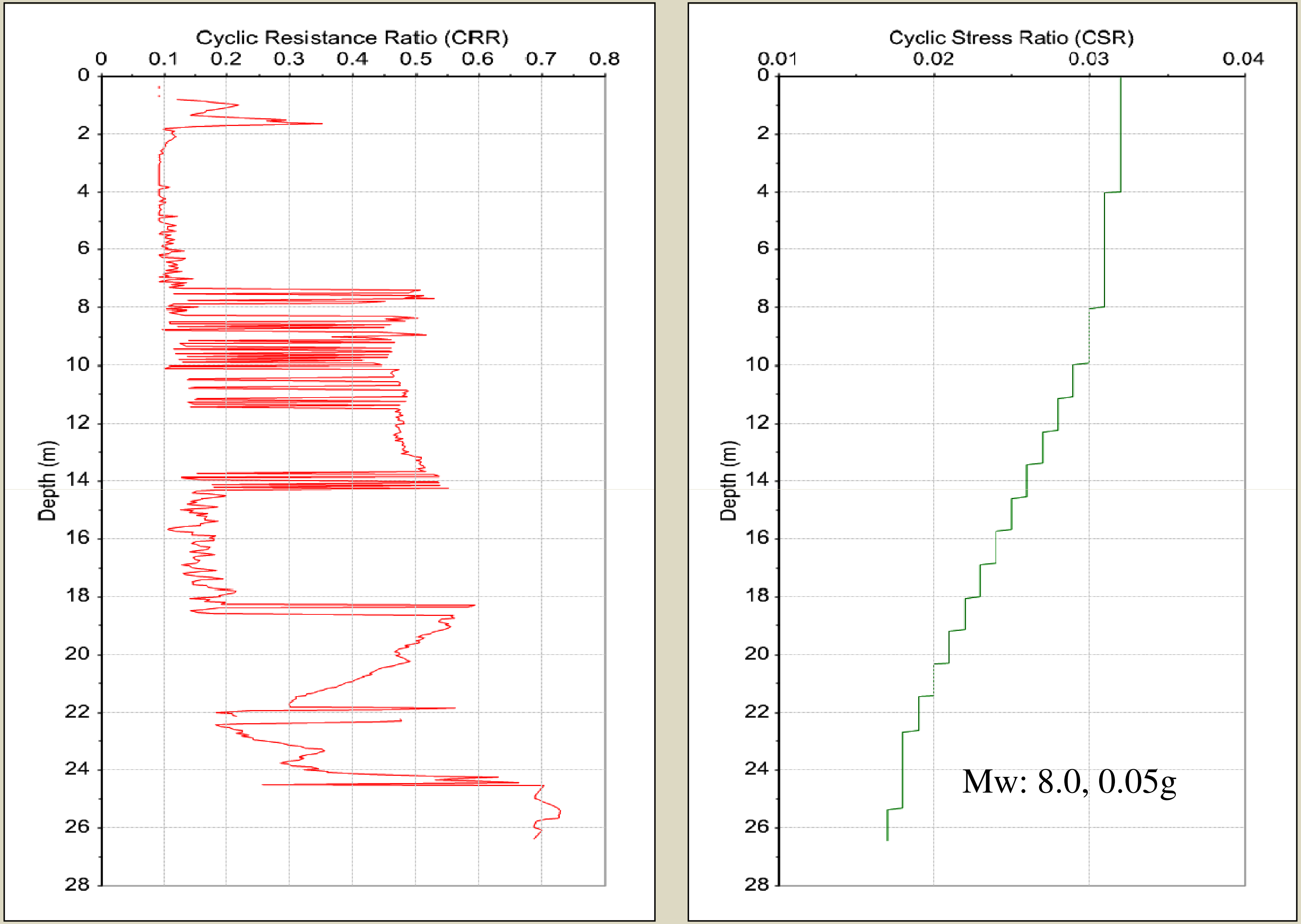
Details of liquefaction triggering analysis showing CRR, CSR and Safety Factor of reclaimed area in east of Singapore.

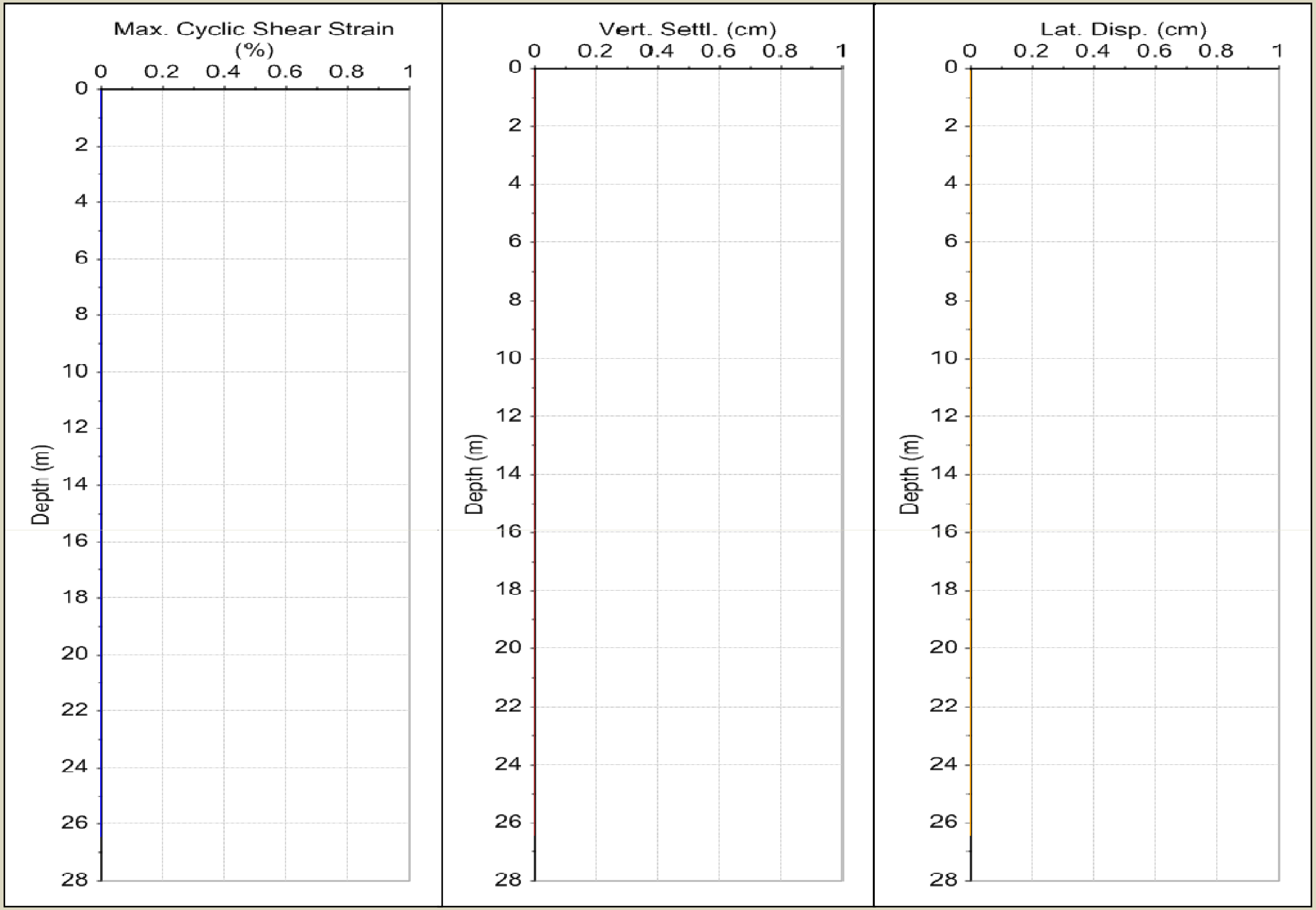
Soil profile of reclaimed area in east of Singapore.

A CPT Liquefaction Analysis

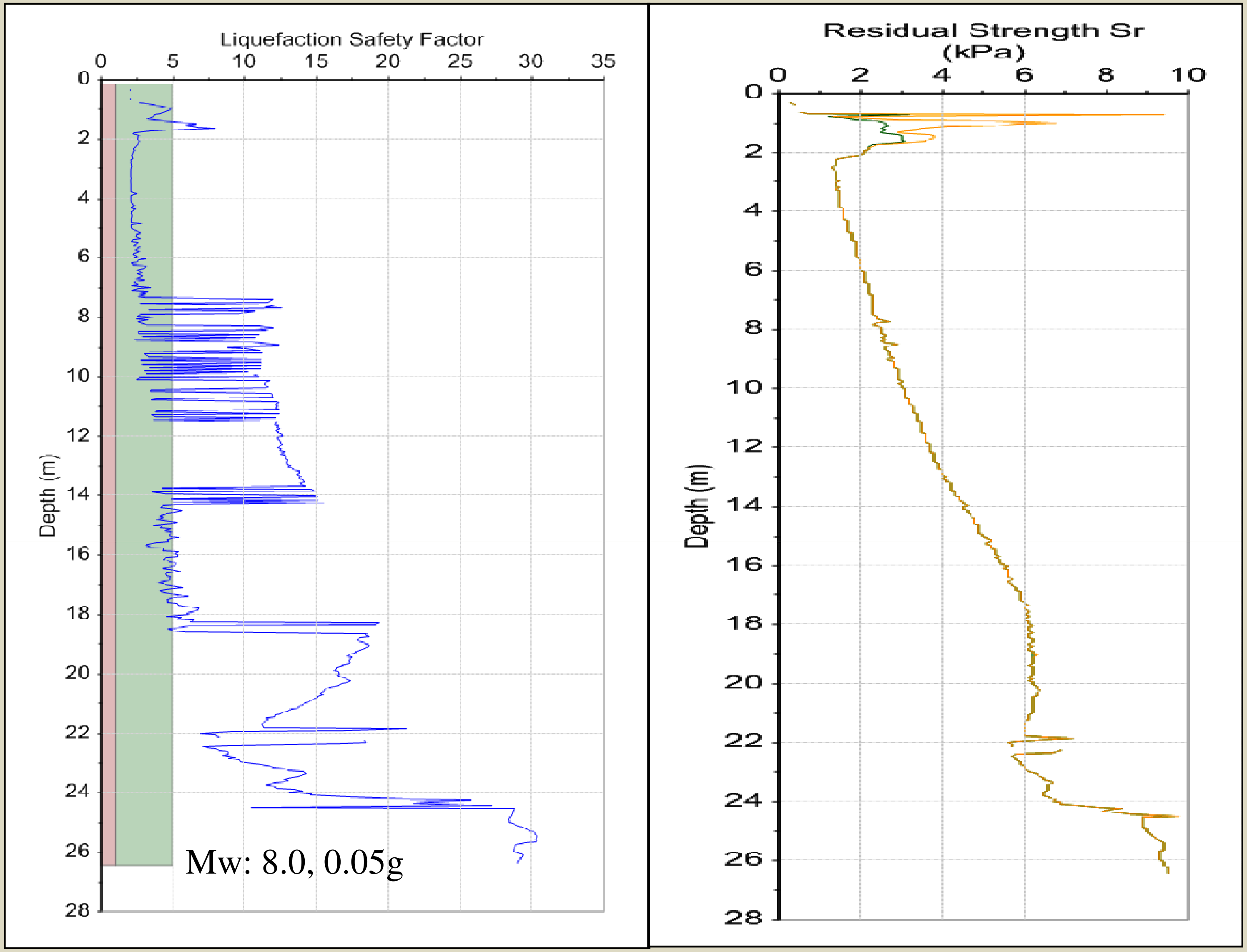


Soil behaviour type chart for soil layers in reclaimed area in east of Singapore.


Cyclic Resistance Ratio (CRR)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Depth (m)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28
Cyclic Stress Ratio (CSR)
0.01 0.02 0.03 0.04
Depth (m)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28
Mw: 8.0, 0.05g



Mw 8.0/0.05g earthquake would not create any significant damage.



Liquefaction safety factor and residual shear strength in soil layers of reclaimed area, east of Singapore.

Comments

Liquefaction analysis results, particularly ***settlement and lateral displacement, and safety factor*** show that in the event of a big earthquake somewhere in Sumatra, Indonesia we may feel the tremors but our foundations in reclaimed land shouldn’t have significant damage.

Therefore, this geotechnical observation supports the fact that Singapore geologically situated behind the back arc basin is tectonically safe haven.

THANK YOU

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