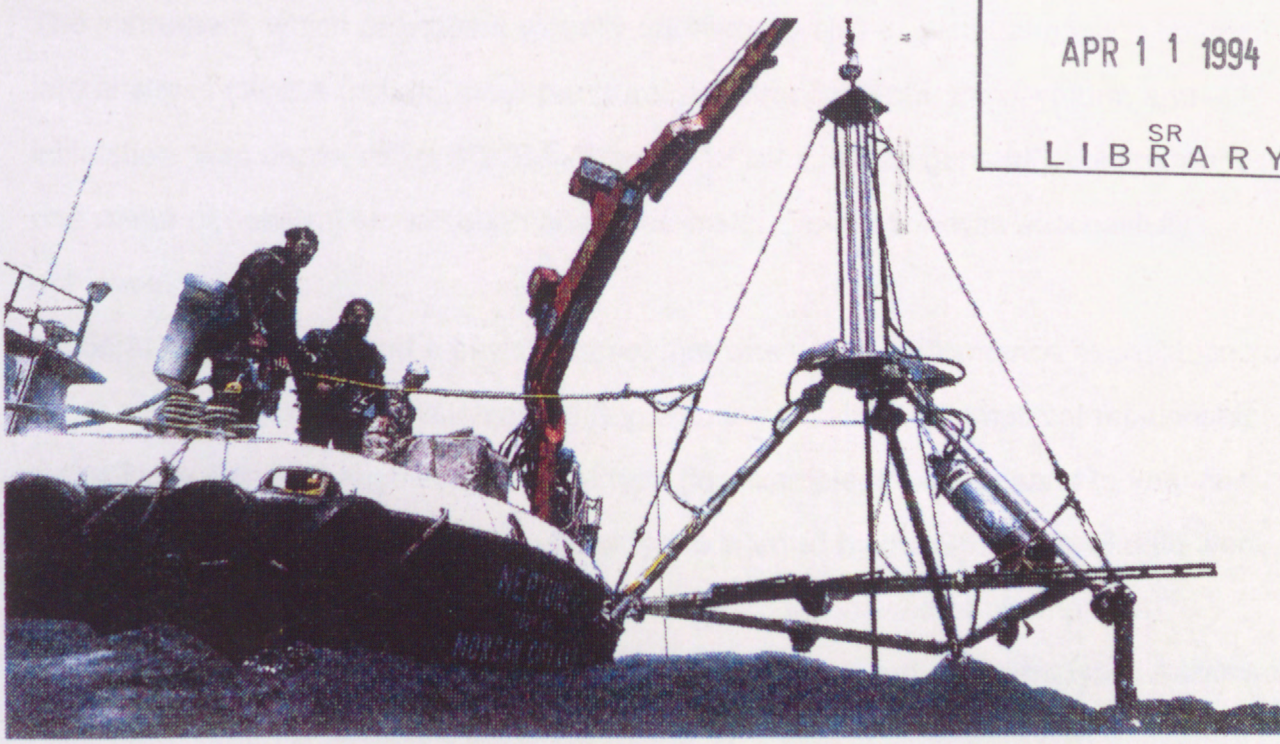
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Evaluation of SEAPCONE Performance in the Nearshore Lakebed off Illinois Beach State Park, Lake Michigan

James S. Booth and William J. Winters

Open-File Report 93-711



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ABSTRACT

Initial tests of the U.S. Geological Survey cone-penetrometer system (SEAPCONE) were conducted in Lake Michigan in waters 4 to 10 m deep off Illinois Beach State Park. The instrument, which provides a virtually unbroken profile of penetration resistance, lateral stress (sleeve friction), pore pressure, penetration depth, temperature, and inclination, was deployed by SCUBA divers at 12 sites. It was generally configured for one meter of penetration, although one three-meter penetration was successfully achieved.

SEAPCONE generated a basic data set that was within performance expectations of other cone penetrometer systems and fit previously established empirical relationships. Specifically, minor changes in sediment type (for example, from fine sand to very fine sand) were easily detected and sediment types inferred by the SEAPCONE data were close to or within the proper ranges as based on published charts of empirical relationships between cone penetrometer test (CPT) data and sediment type. A lakeward trend of decreasing grain size indicated by the CPT data is consistent with measured and published grain size data from the area. Moreover, a downhole fluctuation in friction ratio at 3 sites along one transect suggest that, although there is no independent corroboration with grain size or other data, a discrete, interbedded layer can be readily detected. Finally, the engineering data relating to bearing capacity, including pore pressure, is reasonable for these sandy sediments.

The initial test of SEAPCONE was encouraging. Laboratory tests are required to ensure versatility in a variety of field environments. In addition, the detection and identification of thin, interbedded lithologies must be certain if the system is to be of primary value as a stratigraphic tool in coastal research. More laboratory testing and field testing (in conjunction with vibracoring) is proposed to fully develop SEAPCONE's potential.

INTRODUCTION

An inexpensive, sea-flloor cone-penetrometer system capable of being deployed off small vessels was specially developed to facilitate the U.S. Geological Survey coastal program. The instrument system (SEAPCONE for sea-floor sitting piezometric cone penetrometer system) is suited for framework, erosion, sand and gravel resources, and preliminary engineering studies. More specifically, by providing data pertinent to lithology, stratigraphy, relative density, and other properties, SEAPCONE data foster an understanding of erosion potential, thickness of sand bodies, cyclic and other geological events, liquefaction potential, and other factors that may bear on coastal zone management decisions.

SEAPCONE (Fig. 1) consists of a rod assembly of variable length fronted by an instrumented cone that records resistance to penetration. Elements in and behind (i.e., above) the cone measure pore pressure and a sleeve provides data on sediment friction. Temperature and inclination are also recorded during penetration. The prototype could be rigged to penetrate up to 5 m with the assistance of divers. Winters and others (1993) describe the instrument and its capabilities in detail.

The purpose of this first field test was to evaluate the basic performance of SEAPCONE, particularly as it pertained to further development, and to describe sediment types and stratigraphy of the nearshore area off Illinois Beach State Park, Illinois.

SETTING

The initial deployment of the instrument was in waters from about 4 to 10 m deep off Illinois Beach State Park, Illinois (Fig. 2). The nearshore zone lakebed off Illinois Beach

State Park is a mixture of sands that are a part of the littoral drift system (mostly restricted to well-shoreward of the 6-m isobath) and a regional sheet of fine to very fine sands that originated as a glacial lake plain (Willman and Frye, 1970). This relict sand sheet extends offshore more than 3 km (Fraser and Hester, 1974; Welkie and Meyer,1982). A profile from 1991 based on sub-lakebed refusal depth of an hydraulic jetting system indicates a sand thickness of 3–4 m to a water depth of about 6 m in our study corridor (Shabica and Pranschke, 1993).

Although rapid retreat and accretion have been pervasive in shoreline areas near the study area — as much as 300 m of retreat in an area 2-3 km north and as much as 400 m of accretion in an area 4-5 km south during the past century — the shoreline within the study area has been, by comparison, relatively inactive. Since 1872, this section of shoreline has shown an average net retreat of about 100 m, or ≈1 m/yr (M. Chrzastowski and P. Terpstra, Illinois State Geological Survey, unpublished data, 1992).

The wave climate in this area of Lake Michigan can be characterized as principally low-energy. Calm conditions (waves <1 m in height) are present more than 90% of the time, although hindcast wave statistics (Hubertz and others, 1991) indicate that waves as high as 6.6 m (significant wave height) are possible in the study area, and waves 3-m high may occur yearly. According to Booth (in press) the inner part of the study area may experience active littoral drift about or less than 25% of the time; in the deeper part of the study area (≈10 m), wave-induced drift may occur only 10% of the time. Shore ice, including anchor ice, ice ridges and other components of the nearshore ice complex, although an important component of the geologic setting in the region (Barnes and others, in press), does not generally extend lakeward far enough to influence the lakebed over that portion of the nearshore zone defined for this field test; that is, to a minimum water depth of about 4 m, which is about 200 m offshore.

METHODS

Field

Cone-penetrometer tests with pore pressure measurements (CPTU) were completed at 12 stations in July, 1991 using the R/V Neptune as a platform and SCUBA divers to deploy, operate, and recover the instrument. Figure 3 shows a deployment of the system. The sensors were hard-wired to a computer in a shipboard laboratory, where the real-time data acquisition was monitored. Data were collected from nine channels:

1. Time
2. Penetration depth
3. Cone bearing (tip resistance)
4. Sleeve friction
5. Pore pressure
6. Penetrometer inclination
7. Temperature
8. X-axis platform tilt
9. Y-axis platform tilt.

Penetration rate was approximately 2 cm/s and data collection rate was 10^3 samples/channel/second. Although a penetration of 3 m was achieved in a special test, the penetrometer was otherwise configured for a 1-m penetration. Results are presented to the 1-m penetration depth.

Three, shore-normal tracks were run with stations set at 4, 6, 8, and 10-m water depths on each track (individual tracks are color-coded on Fig. 4a). Loran C was used for establishing position after the penetrometer system was on the lakebed, and a correction was made for the offset between the antennae location and the tripod. One set of station locations (1, 2, 3, 4) was also established with laser positioning in the event that future (serial) sampling became desirable. Diver cores were also collected at each site for stratigraphic description and grain size analysis. Furthermore, divers' observations of each lakebed site were recorded.

<u>Laboratory</u>

The CPTU field data (≈100 MegaBytes) were reduced to approximately 500 readings for each channel per meter for each of the 12 sites. Corrections for cone resistance and sleeve friction values were made by subtracting the average value for each channel recorded during the pretest time interval (as the tripod sat on the lakebed before actual lakebed penetration) from the remainder of the readings. This correction was typically on the order of 1% of the highest absolute value recorded during an individual test sequence for the tip data, and up to 20% to 40% for the friction data, which are characteristically less accurate and prone to being more erratic than the tip data (Robertson and Campanella, 1986).

CPTU profile interpretation necessitates certain data filtering and editing procedures. First, because the tip senses the interface as much as 10 cone base diameters (cone base diameter = 2.53 cm; therefore ≈25-26 cm) below and above its stratigraphic position (Schmertmann, 1978), and because the cone and pore pressure element must be fully embedded in the lake floor (≈3 cm) before this "influence" factor can be accounted for, we conservatively truncated the top 30 cm of all tip resistance profiles. Secondly, because there is a ≈6 cm offset between the cone and the friction sleeve, the top ≈36 cm of the friction sleeve profiles were not used. Also, the bottom 6 cm of each friction sleeve profile had no corresponding tip values because of the vertical offset between the two sensors. It also was not used. Although cone-resistance and friction values are affected by excess pore pressure (hydrostatic pressure greater than the pressure attributable to water depth), corrections were not necessary in this study because excess pore pressures were nonexistent or insignificant in these sands. Accordingly, pore pressure, along with temperature and data related to cone inclination during penetration, which was always less than 2°, are not presented. Further, the data were not standardized with respect to increasing overburden (see, for example, Wroth, 1984). All cone bearing stress profiles are presented in Appendix A.

Samples were taken at 1-cm-intervals from eight diver cores for grain size analysis, which was accomplished using a rapid sediment analyzer and a Coulter Counter (see Poppe, 1988).

RESULTS AND DISCUSSION

Factors that affect CPTU data

Although equipment design and rate of penetration may affect absolute values of the cone tip data, those factors that can control profile shape; that is, relative changes in cone resistance downhole, are geological. These factors, along with an example of their effect, are listed in Table 1.

Table 1

Common factors affecting cone penetration resistance and an example of their effect

FACTOR	IF IT WERE TO	CONE TIP RESISTANCE WOULD
Overburden	increase	increase
Bulk density	increase	increase
Grain size	increase	increase
Cementation	increase	increase
Compressibility	increase	decrease
Lateral stress	increase	increase

These factors are not necessarily mutually independent, which raises considerable uncertainty in the profile interpretation in the absence of other site information. Moreover, penetration through discrete layers may not engender a full response by the instrument if the layers are thin, because interbedded units, if less than 10 to 20 cone diameters (as much as 50 cm thick for SEAPCONE), are thinner than the vertical zone of influence that may act on the tip (Robertson and Campanella, 1986). It follows that cone penetrometer data tend to present a smoothed (or averaged) profile that can somewhat mask interlayering unless the associated downhole changes are abrupt and significant. This smoothing phenomenon is enhanced when going through a stiffer layer because the tip influence distance increases with sediment stiffness, and is diminished when passing through a softer layer. In increasing contrast, the friction sleeve is only influenced over its actual length (9.5 cm) and therefore is more sensitive to thinly layered units and a piezometric element can significantly reduce the thickness of sediment layers that are distinguishable from CPTU data. However, to even further complicate interpretation, sand units, due to their natural variability, tend to cause saw-tooth profiles (Robertson and Campanella, 1986).

It is within this set of caveats that numerous empirical or semi-empirical relationships between CPTU results and sediment types have been tentatively set forth (e.g., Douglas and Olsen, 1981; Robertson and others, 1986; Robertson, 1989). Because these published relationships, which are based on plots of cone bearing vs. friction ratio percentage, were only intended to provide global guidelines for interpretations rather than locally accurate classification, and thus are conservative, it was imperative that the SEAPCONE data plotted within or at least proximal to the boundaries previously established for each sediment type. Otherwise, SEAPCONE's value as a research tool in coastal waters would be reduced from the status of providing stratigraphic information in the sense of indicating sediment types to that of an indicator of relative downhole changes in sediment properties until further testing and calibration could be done.

The nearshore zone off Illinois Beach State Park was an accommodating environment for this initial test because it comprises a simple stratigraphy. Also, because the depth of penetration of the instrument into the lakebed was relatively shallow (≈1 m) and the lakebed is unconsolidated, cohesionless quartzose sand (Fraser and Hestor, 1974), anomalous lateral stress, abnormal compressibility, and cements are probably not significant factors with respect to CPTU results. Therefore, our interpretations are guided by an obvious increase in overburden stress (σ'_v) downhole, which causes an increase in both tip resistance and sleeve friction with depth, and changes in grain size and bulk density. Accordingly, we term the profile traces as representative of "geotechnical" stratigraphy, in that they are based on geotechnical data (i,e,. sediment mass physical properties), but suggest that they correlate closely with grain size parameters.

Establishing the texture of the sediments to a depth of 1 m below the lakebed to validate the performance of SEAPCONE as a sediment classification tool could not be fully realized because of limitations in the diver coring operation: the longest diver core was <50 cm and all but three cores were less than 36 cm long. However, evidence such as the general persistence of a simple grain-size spatial distribution pattern, which is manifest both in the surface sediment (Fig. 4b) and in the sublakebed (Fig. 5), along with the findings of Fraser and Hester (1974), who sampled to a sublakebed depth of 3 m in the vicinity of the northernmost set of sites and found a consistent grain size (very fine sand) throughout the column, does not intrinsically imply that a widespread presence of an interbedded or complex substrate within the upper meter of sediment is to be expected. Consequently, and despite the fact that an absolute absence of stratigraphic changes in the upper meter cannot be verified, an indication by the SEAPCONE data of the presence of fine to very fine sands[1] would be tentatively considered a successful performance test.

Grain size classification based on CPTU data

The basic grain-size classification scheme of Robertson and others (1986) is shown in Figure 6. The region of the chart that is most applicable to these Lake Michigan sands as a whole is represented by the cluster of points associated with Seapcone Site 1 (Fig. 6a). That is, almost all samples in this study show a friction ratio percentage of <1% and a cone bearing between 1 and 10 MPa. This, in turn, classifies most of the lakebed sediment as sand to silty sand. Specifically with respect to Site 1, which does have some grain size data to compare directly with the data point locations on the classification chart, the SEAPCONE has slightly underestimated grain size. At Site 2 a vertical trend in the cone bearing values is evident (Fig. 6b). This reflects a persistent increase in cone bearing with penetration depth; that is, with increased overburden. This trend is pervasive at the remainder of SEAPCONE sites and underscores the fact that the data are not normalized. A comparison of Site 1 and Site 2 plots (Fig. 6a and 6b) reveals that the sediments at Site 2 are slightly coarser. Similarly, the SEAPCONE data suggest that the sediments continue to become coarser in sequence through Site 3 to Site 4 (Fig. 6c and 6d). This pattern is shown in the other transects as well: Sites 5–8 (Fig. 6e–6h) and Sites 10-12, 9 (Fig. 6i-6l) show an increase in grain size from a silty sand to a sand from 10 m to 4 m water depth. The composite results of the sediment classification plots are represented in Figure 7 on the basis of water depth vs. sediment type. This trend is in accord with that indicated by grain size analysis (Fig. 5), and thus establishes a fundamental level of relative integrity of the SEAPCONE as a predictor of sediment type.

Another trend revealed by the comparison of SEAPCONE data and grain size analysis addresses the question of absolute integrity of the SEAPCONE as a classification tool, at

[1] The boundary between sand and silt size is placed at 3.75ø in this report (rather than 4ø as in a conventional geological context) because the published classification chart (Robertson and others, 1986) was constructed within a civil engineering context.

least with respect to the classification fields constructed by Roberson and others (1986). The comparison shows that the SEAPCONE data tend to slightly underestimate grain size. In addition to Site 1 (mentioned previously), there are two other sites for which grain size analysis exist at a depth valid for comparison to the SEAPCONE data (Site 10 (Fig. 6i) and Site 11 (Fig. 6j)). Both of these also show a slight underestimate of the grain size determined directly from laboratory analysis. Despite this, the grain sizes indicated by the SEAPCONE data are roughly consistent with the grain size analyses and, given the global nature of the classification scheme, we consider the fit adequate. Further field tests and laboratory calibrations may improve the correlation.

Several anomalous sequences are present in the cone bearing-friction ratio data. Most notably, in Sites 6,7 and 8 (Fig. 6f-h), a spike — indicating an increase in friction ratio between 60–80 cm — interrupts the otherwise consistent friction ratio values associated with the constant increase in cone bearing value. Although the deviation is minor, its true magnitude may be somewhat masked by the smoothing effect attributable to the broad zone of cone influence. Thus, the spike may represent a notable change in sediment type or other characteristic. For example, it may indicate the presence of an interbedded finer-grained sediment. In addition, the plot of Sites 10 (Figs. 6i) implies that a very thin layer of stiff, fine sediment (or dense, perhaps overconsolidated material) may exist around 50 cm.

<u>Geotechnical stratigraphy</u>

The composite plot of cone bearing vs penetration depth (Fig. 8) shows the following characteristics:

1. On all profiles the cone bearing value tends to increase with penetration depth.
2. In general, cone bearing decreases in the offshore direction; the 10-m sites show the least resistance to penetration (finer and/or less dense sediment) and the 4-m sites show the most resistance (coarser and/or denser sediment).

Insofar as grain size, bulk density (i.e., unit weight), and overburden are taken as the primary controlling factors of cone bearing values in this study, and assuming that there is not a steady and significant downhole increase in grain size throughout the study area, it is likely that the mostly steady increase in cone bearing with penetration depth reflects the increase in overburden stress. It may also reflect a condition related to an increasing overburden in most unconsolidated sediment columns, particularly in the upper ten meters: an increasing bulk density. In either case, we take the trend as essentially independent of stratigraphic changes in terms of sediment type and view the absolute variability between the profiles as more of an indicator of differences in the sediment. Specifically, the progressive absolute decrease in penetration resistance between the 4-m sites and the 10-m sites, in conjunction with the decrease in grain size (see Fig. 5), indicates that the well-established correlation between penetration resistance and grain size is manifest in these sediments. The downhole variability shown by individual profiles, typically more pronounced in the stiffer sediments, is interpreted as fluctuations in grain population characteristics. In particular, changes in grain size (thin layers of shell-rich sediments as well as other texturally coarser layers and layers of slightly finer sands were identified in the upper part of some sections, and may be present at lower stratigraphic levels) and skewness (some zones in the sediment column indicate that the nearshore zone is occasionally subjected to an abnormal influx of fines — silt and clay-sized particles — which may locally increase bulk density when mixed with the predominant sand-sized population) would seem to be two of the more important of these characteristics.

PERFORMANCE OF SEAPCONE

Despite necessary compromise with well-established land-based design and operational standards in order to function with facility in a subaqueous environment, SEAPCONE provided a basic data set that was within performance expectations of other cone penetrometer systems and fit previously established empirical relationships. Specifically, it performed such that:

1. Minor changes in sediment type (for example, from fine sand to very fine sand) were easily detected.

2. Sediment types predicted by SEAPCONE data were close to or within the proper ranges as based on published charts of empirical relationships between CPT data and sediment type.
3. A downhole fluctuation in friction ratio in 3 sites along one transect suggest that, although there is no independent corroboration with grain size or other data, a discrete, interbedded layer can be readily detected.
4. The engineering data relating to bearing capacity, including pore pressure, is reasonable for these sandy sediments.

Being an initial test of SEAPCONE, the performance of the system off Illinois Beach State was encouraging. Additional laboratory tests are required to ensure versatility in a variety of field environments. Moreover, the detection and identification of thin, interbedded lithologies must be certain if the system is to be of primary value in coastal research. More laboratory testing and field testing (in conjunction with vibracoring) is proposed to fully develop SEAPCONE's potential.

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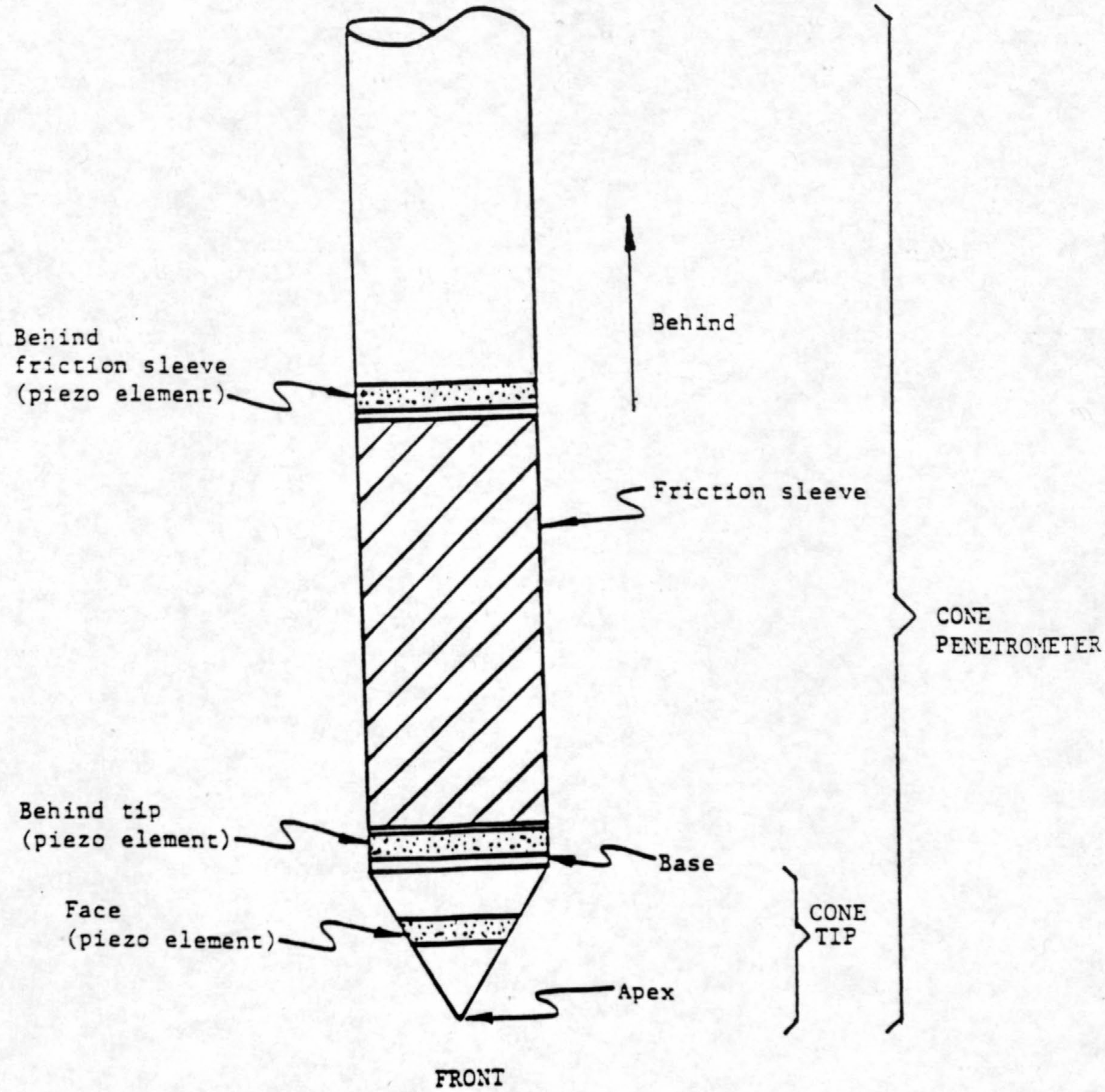
Fig. 1: Schematic of cone penetrometer. Diameter is ≈2.5 cm.



Behind
Behind friction sleeve (piezo element)
Friction sleeve
CONE PENETROMETER
Behind tip (piezo element)
Base
Face (piezo element)
CONE TIP
Apex
FRONT

Fig. 2: SEAPCONE test and study site

STATE LINE
North Point Marina
Winthrop Harbor
0 km 3
0 miles 2
contours in feet
30
24
18
12
6
WI
study area
MI
IL
IN
Zion
ILLINOIS BEACH STATE PARK
STUDY AREA
ILLINOIS
LAKE MICHIGAN
42° 25'
Waukegan
Waukegan Harbor
North Chicago
42° 20'
94
Great Lakes
Naval Training Center
87° 55'
87° 50'
87° 45'

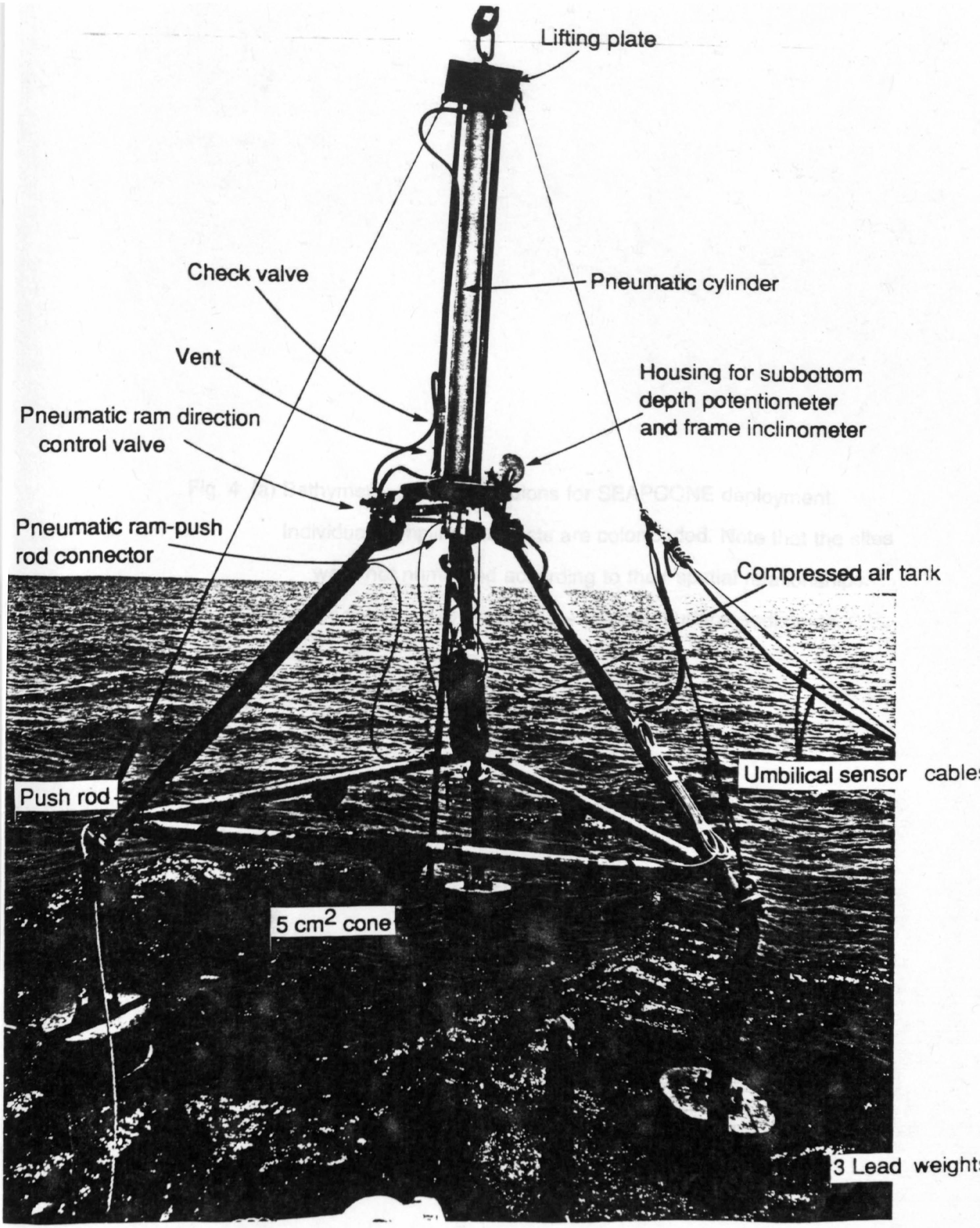
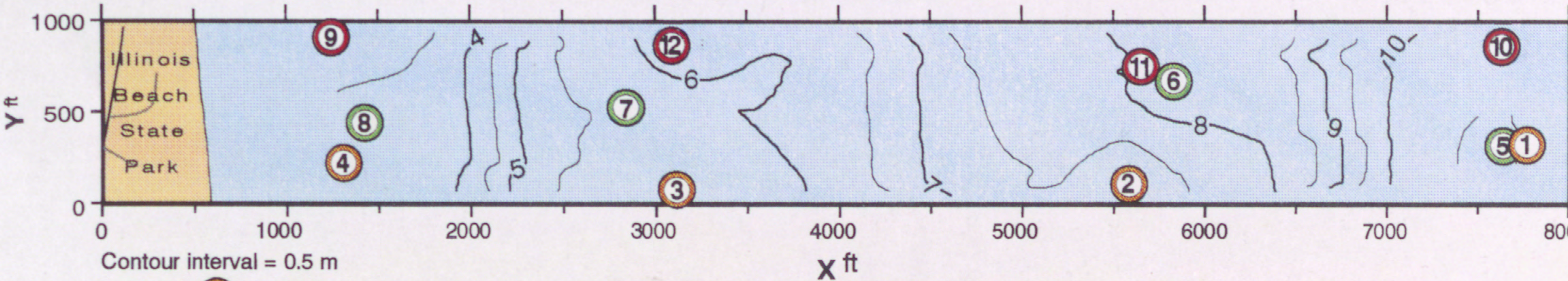

Lifting plate
Check valve
Pneumatic cylinder
Vent
Housing for subbottom
depth potentiometer
and frame inclinometer
Pneumatic ram direction
control valve
Pneumatic ram-push
rod connector
Compressed air tank
Umbilical sensor cables
Push rod
5 cm2 cone
3 Lead weights

Fig. 4 (a) Bathymetry and site locations for SEAPCONE deployment. Individual sampling transects are color-coded. Note that the sites were not numbered according to their spatial relationships.

(b) Mean grain size (ø-units) of the lakebed surface sediments.

ILLINOIS BEACH STATE PARK
In-Situ Study Corridor

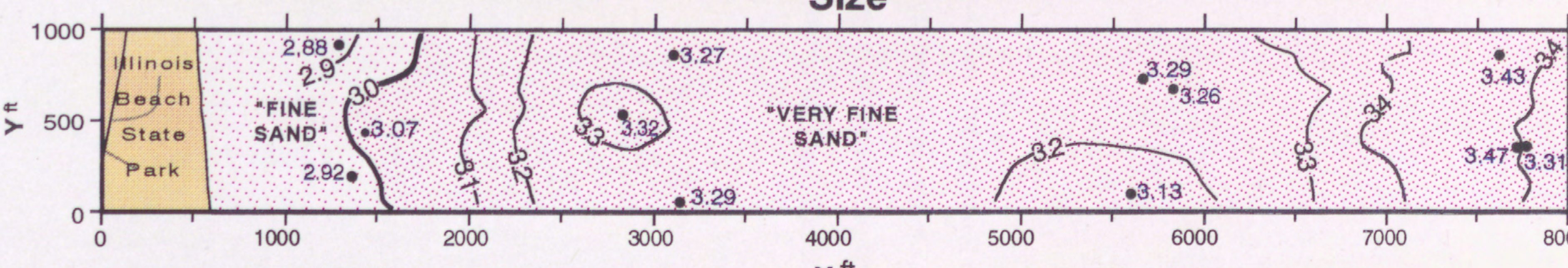
Bathymetry



Contour interval = 0.5 m

Station Location

Mean Grain Size

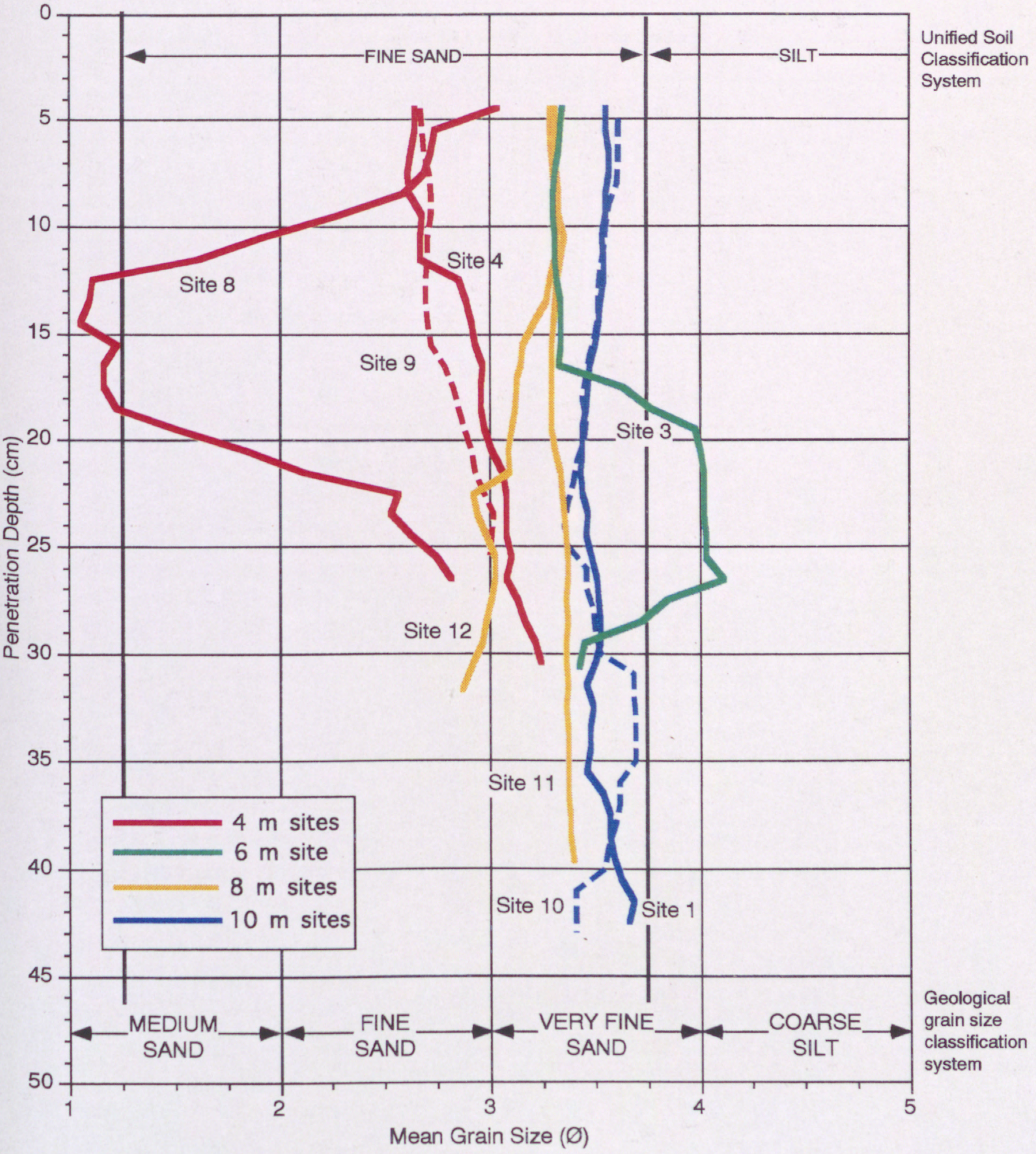


Contours interval = 0.1 Ø units

•3.07
Sample site with ø value

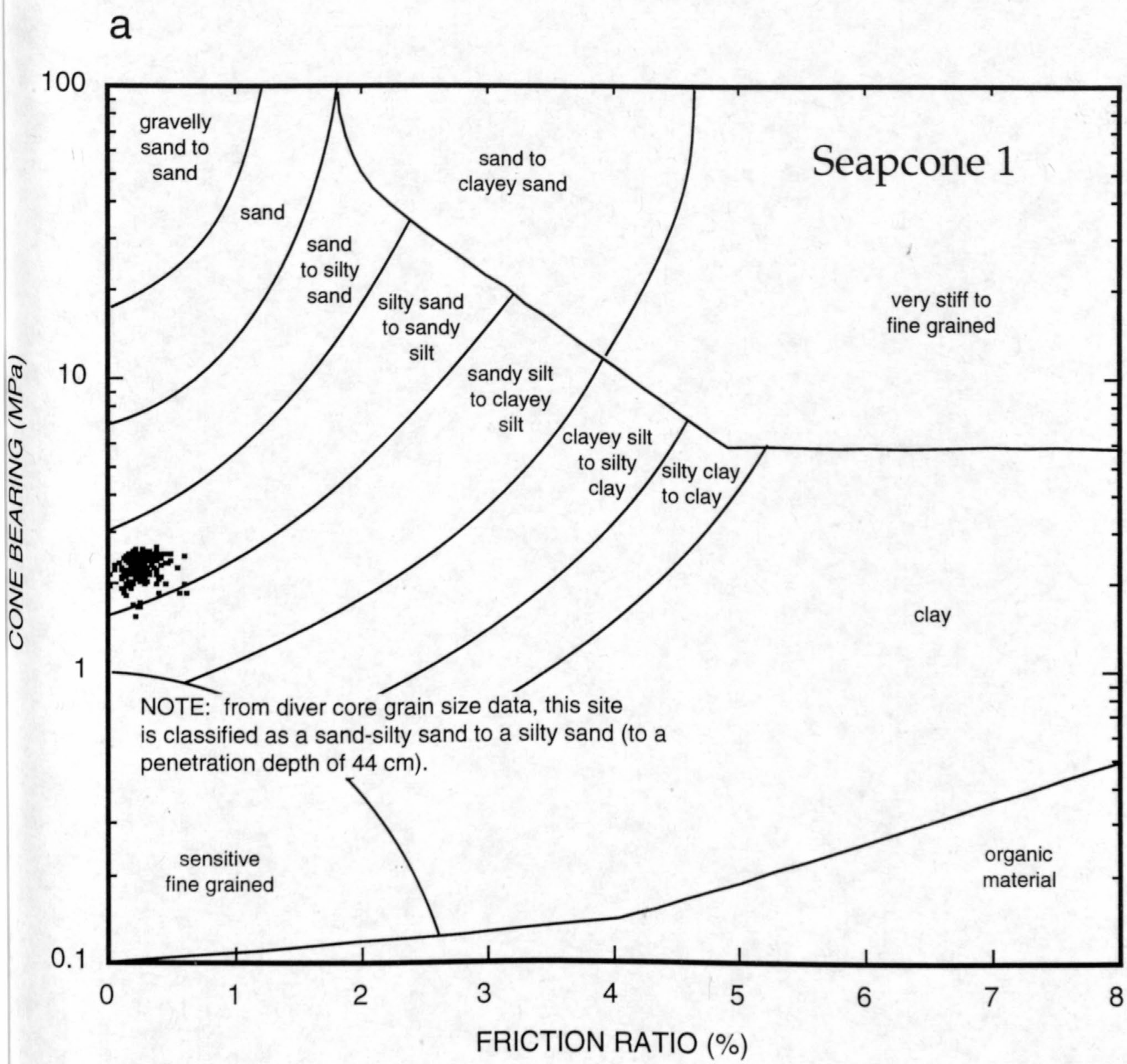
Maps based on Illinois State Plane Coordinate System
X (easting) reference: 642,400 ft = 0 ft
Y (northing) reference: 2,097,830 ft = 0 ft

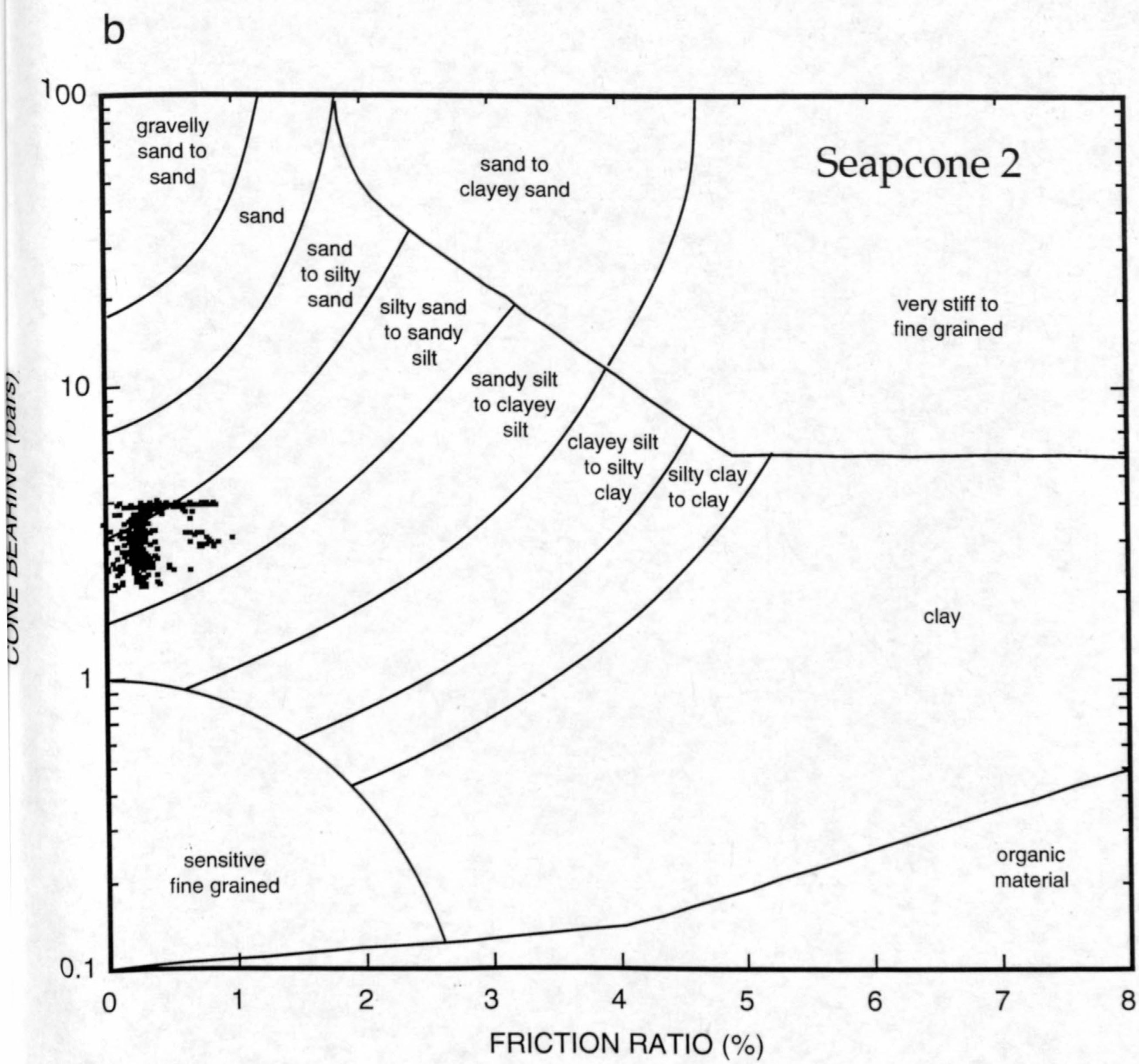
Fig. 5: Sediment mean grain size (ø-units) and sediment classification of diver core samples. Note similarities in texture of samples collected at the same water depth. Note also the difference between geologic and engineering (Unified) classification systems.



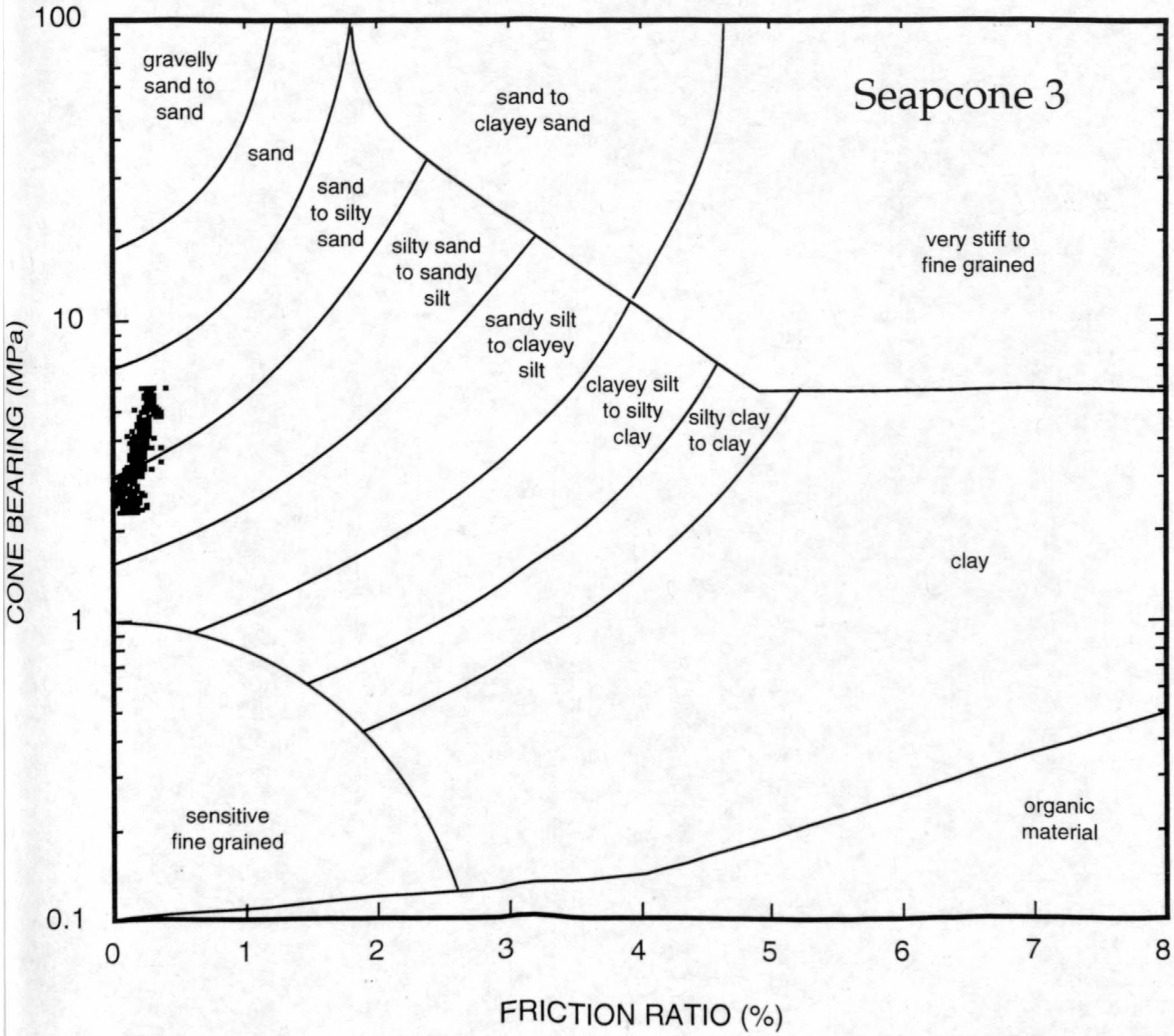
FINE SAND
SILT
Unified Soil Classification System
Site 4
Site 8
Site 9
Site 3
Site 12
Site 11
Site 10
Site 1
4 m sites
6 m site
8 m sites
10 m sites
MEDIUM SAND
FINE SAND
VERY FINE SAND
COARSE SILT
Geological grain size classification system
Penetration Depth (cm)
Mean Grain Size (Ø)
0
5
10
15
20
25
30
35
40
45
50
1
2
3
4
5

Fig. 6 (a-l): Plots of cone bearing vs friction ratio for each site. Sediment classification overlay from Robertson and others (1986). As a generalization, the cone bearing values increase with increasing penetration despite the fact that this is a sediment classification plot. This reflects the fact that the data are not normalized with respect to overburden.

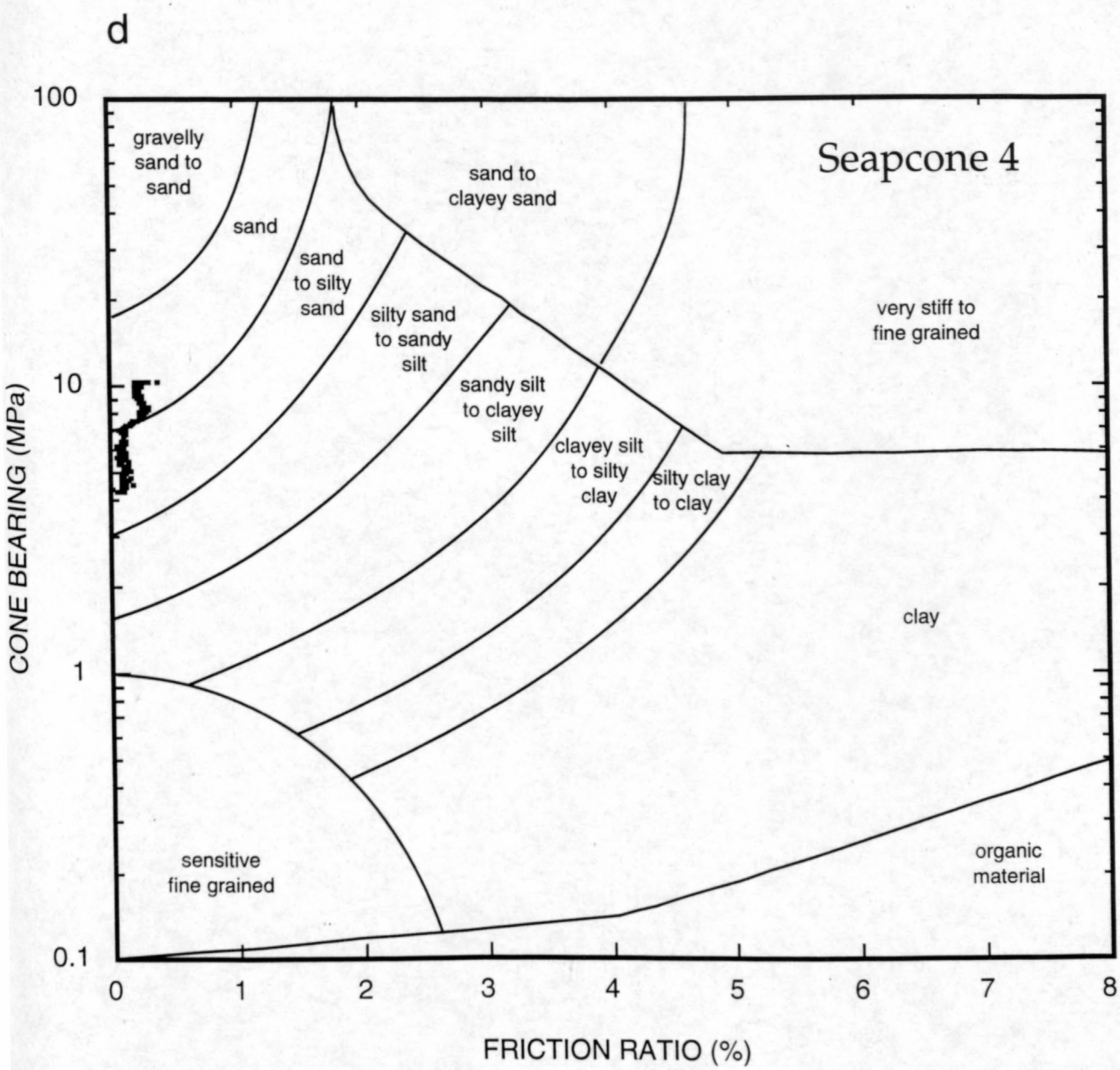

a
Seapcone 1
gravelly sand to sand
sand
sand to silty sand
sand to clayey sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material
NOTE: from diver core grain size data, this site is classified as a sand-silty sand to a silty sand (to a penetration depth of 44 cm).
CONE BEARING (MPa)
100
10
1
0.1
FRICTION RATIO (%)
0
1
2
3
4
5
6
7
8


b
Seapcone 2
gravelly sand to sand
sand
sand to silty sand
sand to clayey sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material
CONE BEARING (bars)
100
10
1
0.1
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)

c

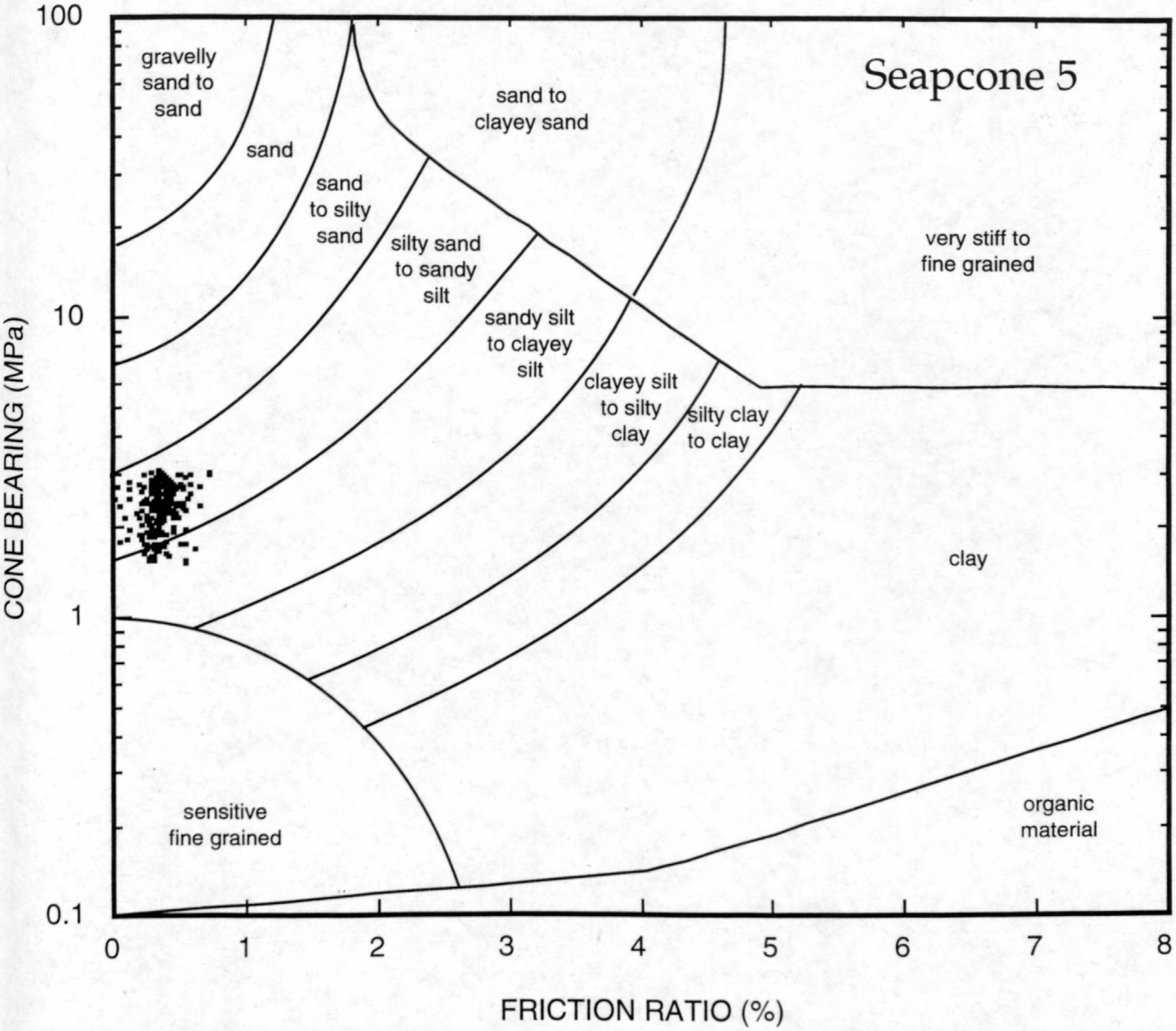


Seapcone 3
100
10
1
0.1
CONE BEARING (MPa)
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)
gravelly sand to sand
sand
sand to silty sand
sand to clayey sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material



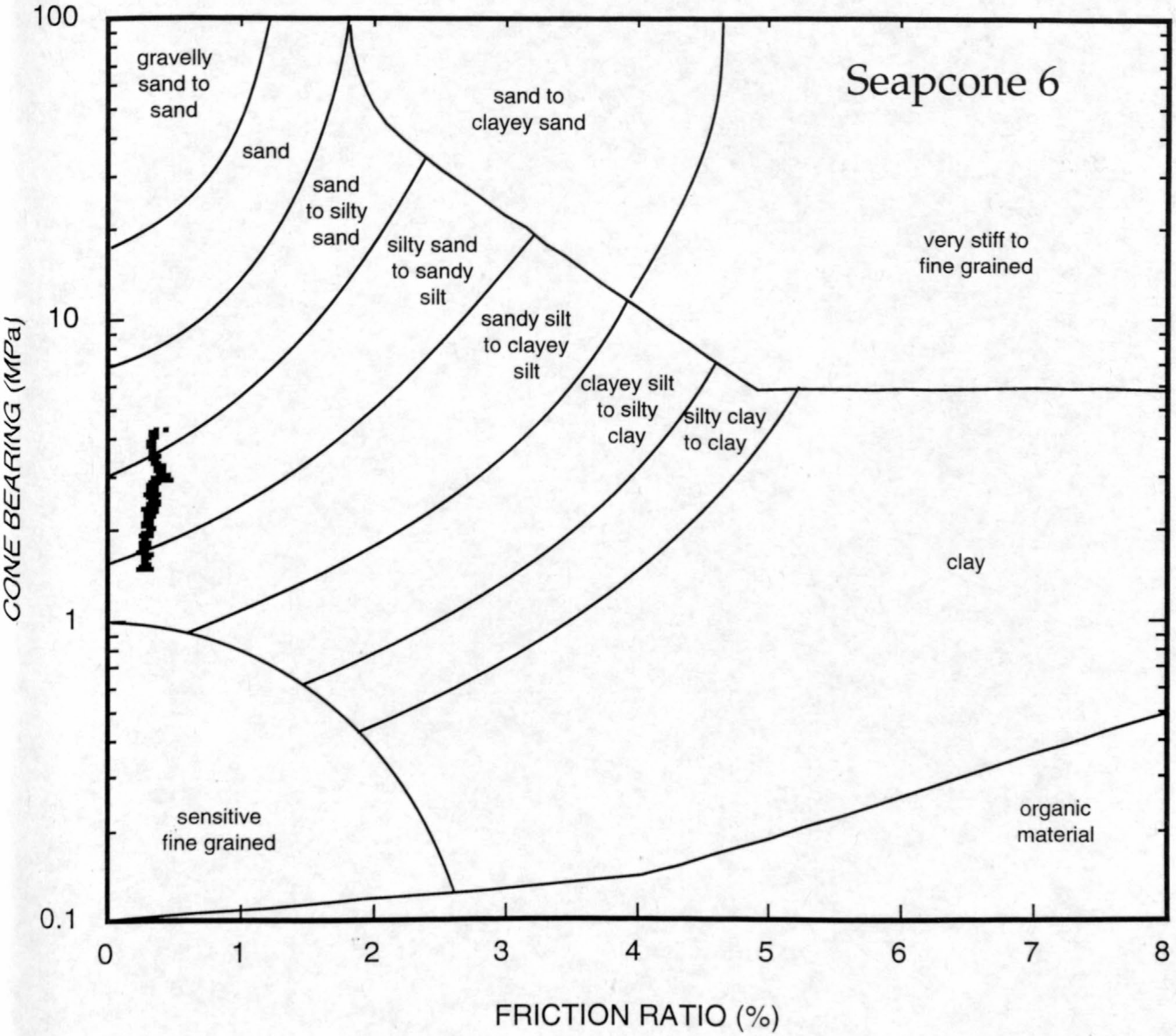
d
Seapcone 4
CONE BEARING (MPa)
FRICTION RATIO (%)
100
10
1
0.1
0
1
2
3
4
5
6
7
8
gravelly sand to sand
sand
sand to silty sand
silty sand to sandy silt
sand to clayey sand
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material

e

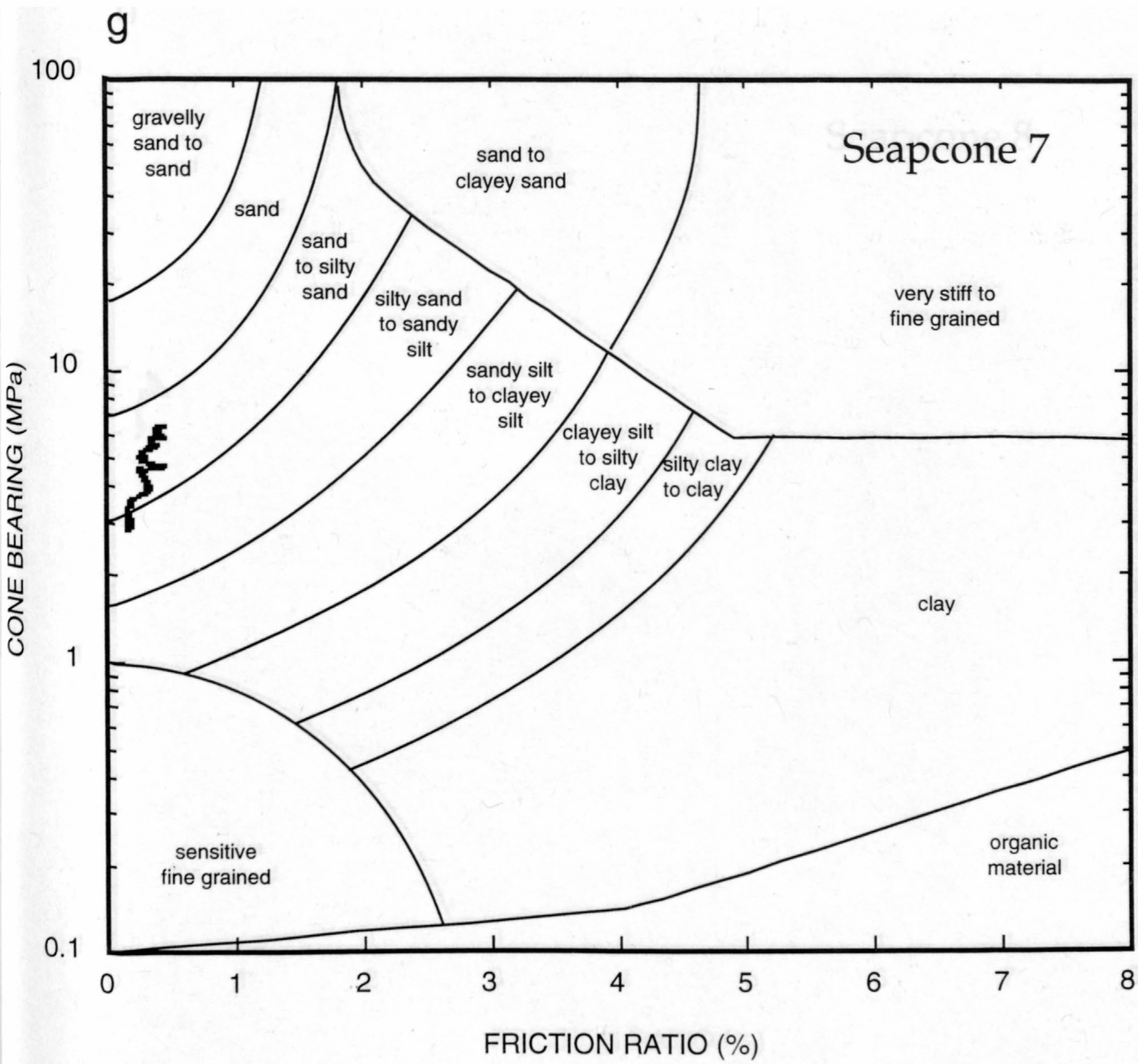


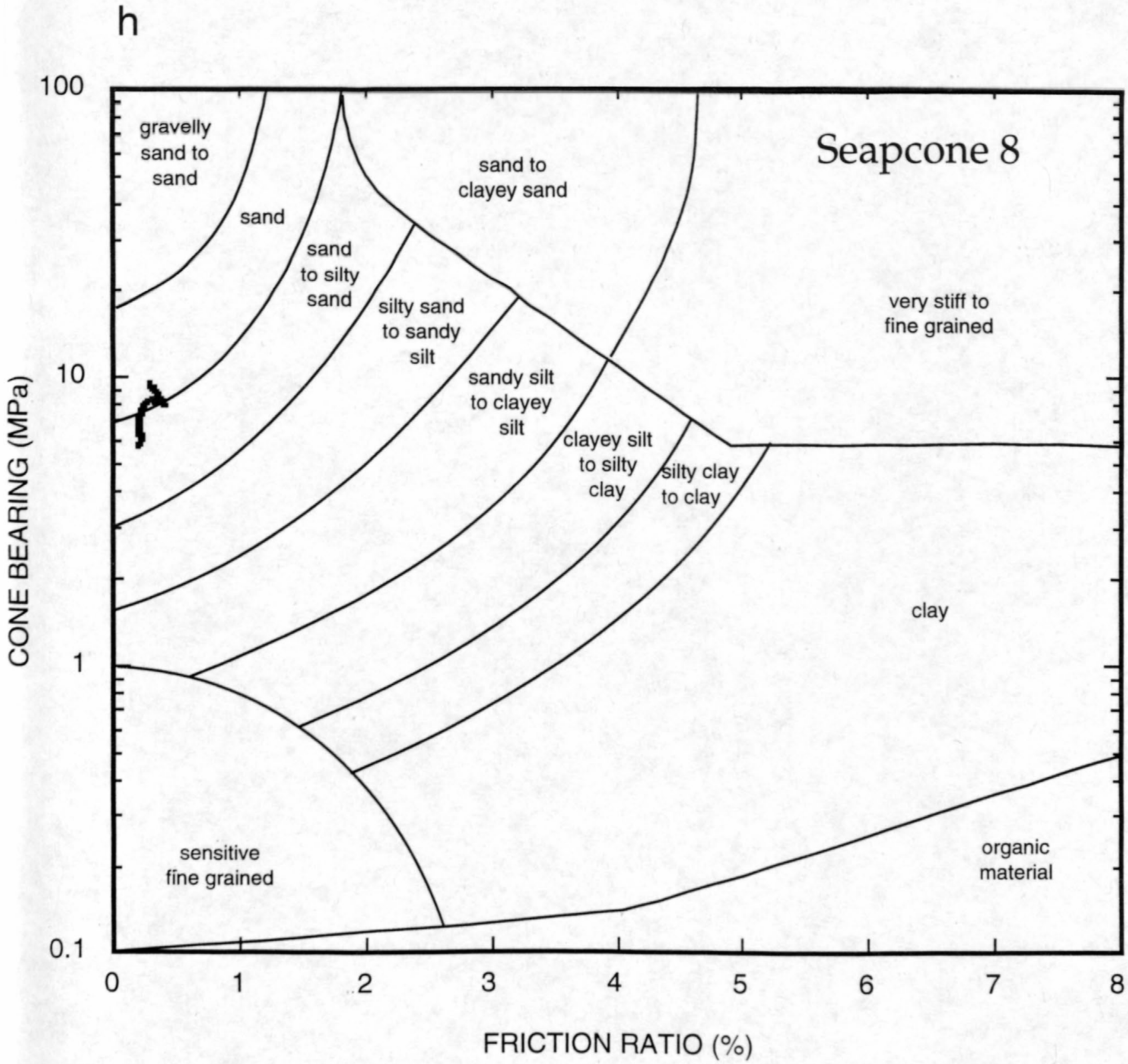
Seapcone 5
100
10
1
0.1
CONE BEARING (MPa)
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)
gravelly sand to sand
sand
sand to clayey sand
sand to silty sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material

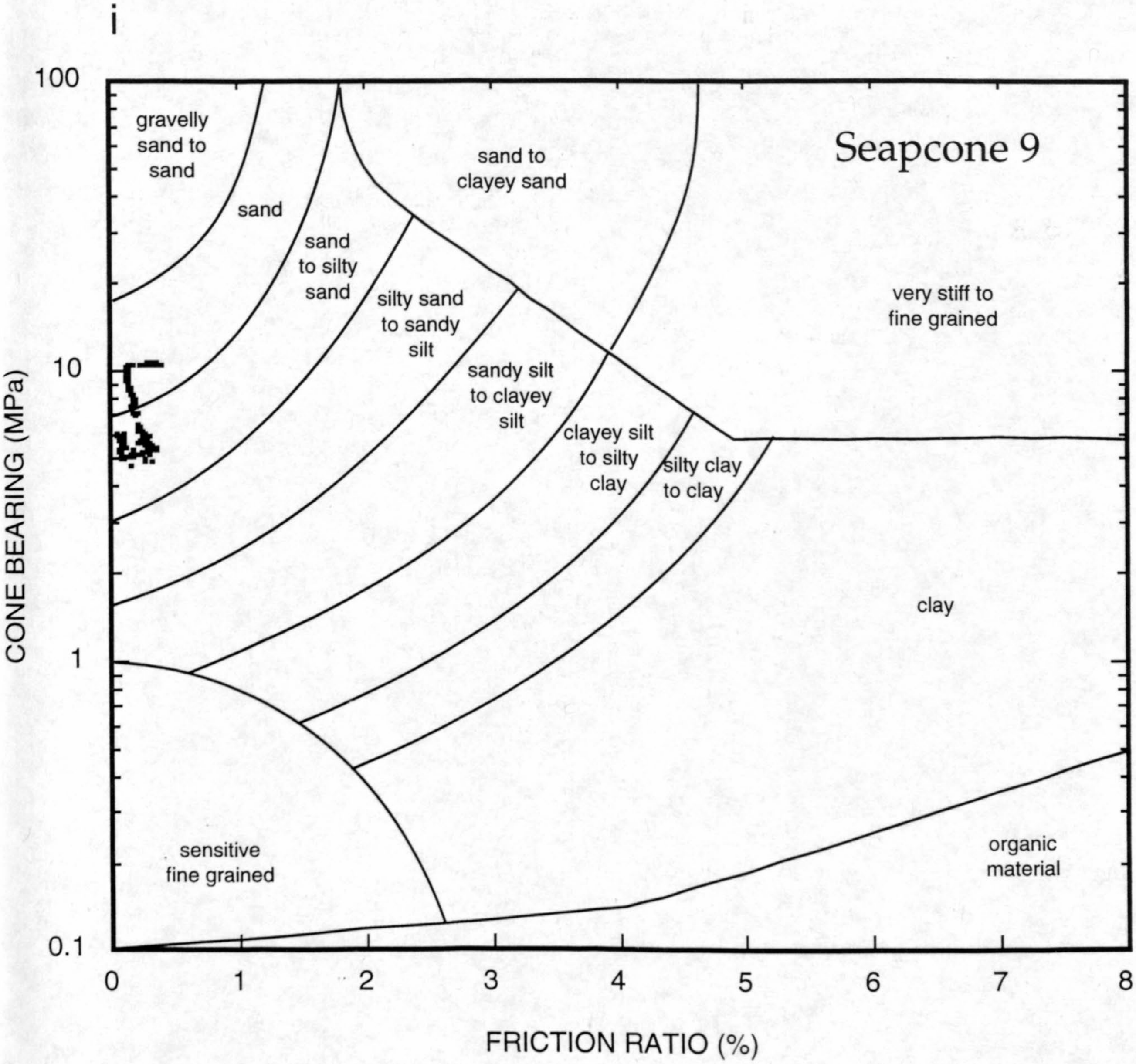
f

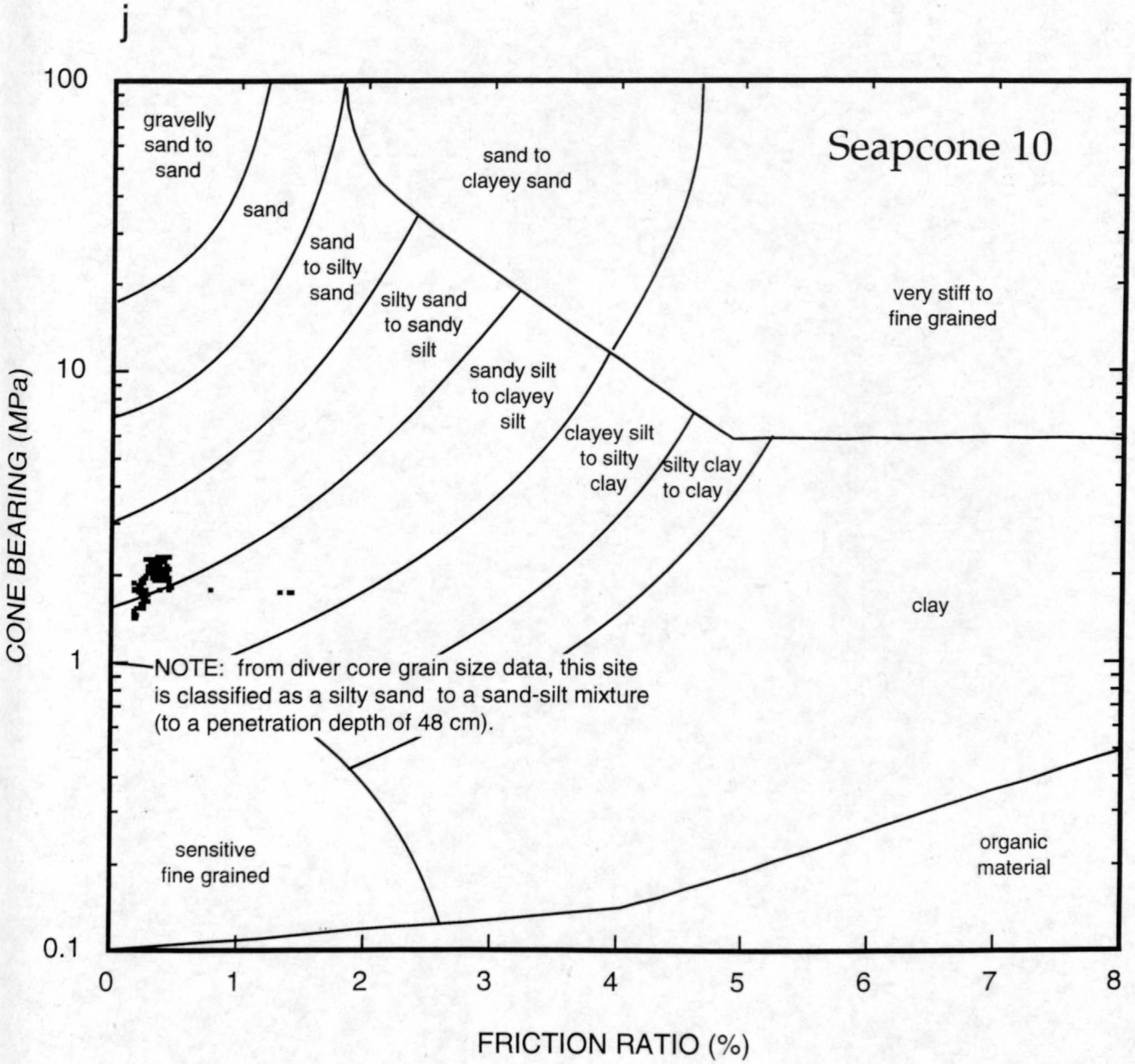


Seapcone 6
gravelly sand to sand
sand
sand to silty sand
silty sand to sandy silt
sand to clayey sand
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material
CONE BEARING (MPa)
FRICTION RATIO (%)
100
10
1
0.1
0
1
2
3
4
5
6
7
8


g
Seapcone 7
CONE BEARING (MPa)
FRICTION RATIO (%)
100
10
1
0.1
0
1
2
3
4
5
6
7
8
gravelly sand to sand
sand
sand to silty sand
sand to clayey sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material

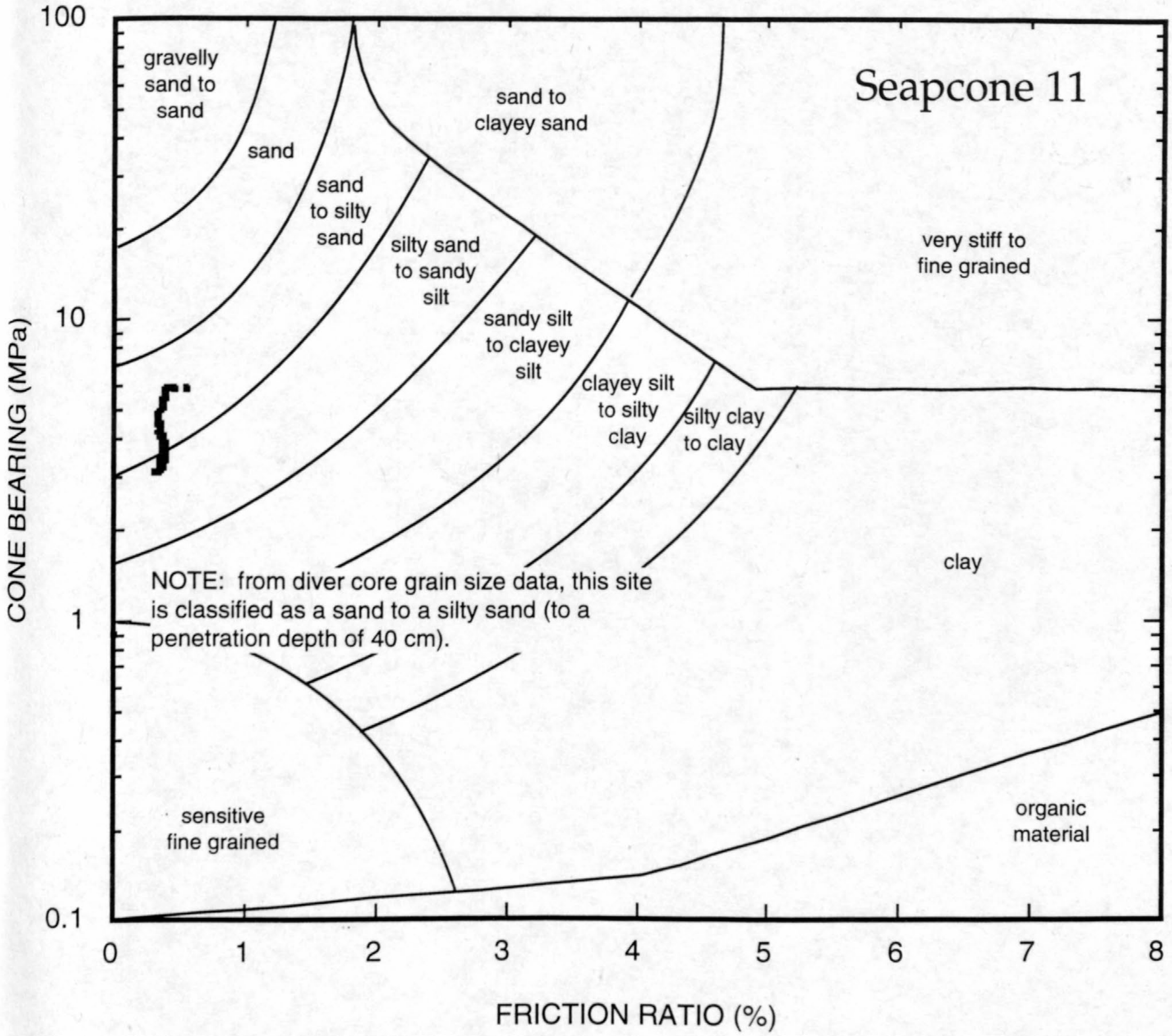

h
Seapcone 8
gravelly sand to sand
sand
sand to silty sand
sand to clayey sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material
CONE BEARING (MPa)
100
10
1
0.1
FRICTION RATIO (%)
0
1
2
3
4
5
6
7
8


i
Seapcone 9
gravelly sand to sand
sand
sand to silty sand
silty sand to sandy silt
sand to clayey sand
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material
100
10
1
0.1
CONE BEARING (MPa)
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)



j
Seapcone 10
gravelly sand to sand
sand
sand to clayey sand
sand to silty sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material
NOTE: from diver core grain size data, this site is classified as a silty sand to a sand-silt mixture (to a penetration depth of 48 cm).
CONE BEARING (MPa)
100
10
1
0.1
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)

k


Seapcone 11
100
10
1
0.1
CONE BEARING (MPa)
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)
gravelly sand to sand
sand
sand to silty sand
sand to clayey sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material
NOTE: from diver core grain size data, this site is classified as a sand to a silty sand (to a penetration depth of 40 cm).

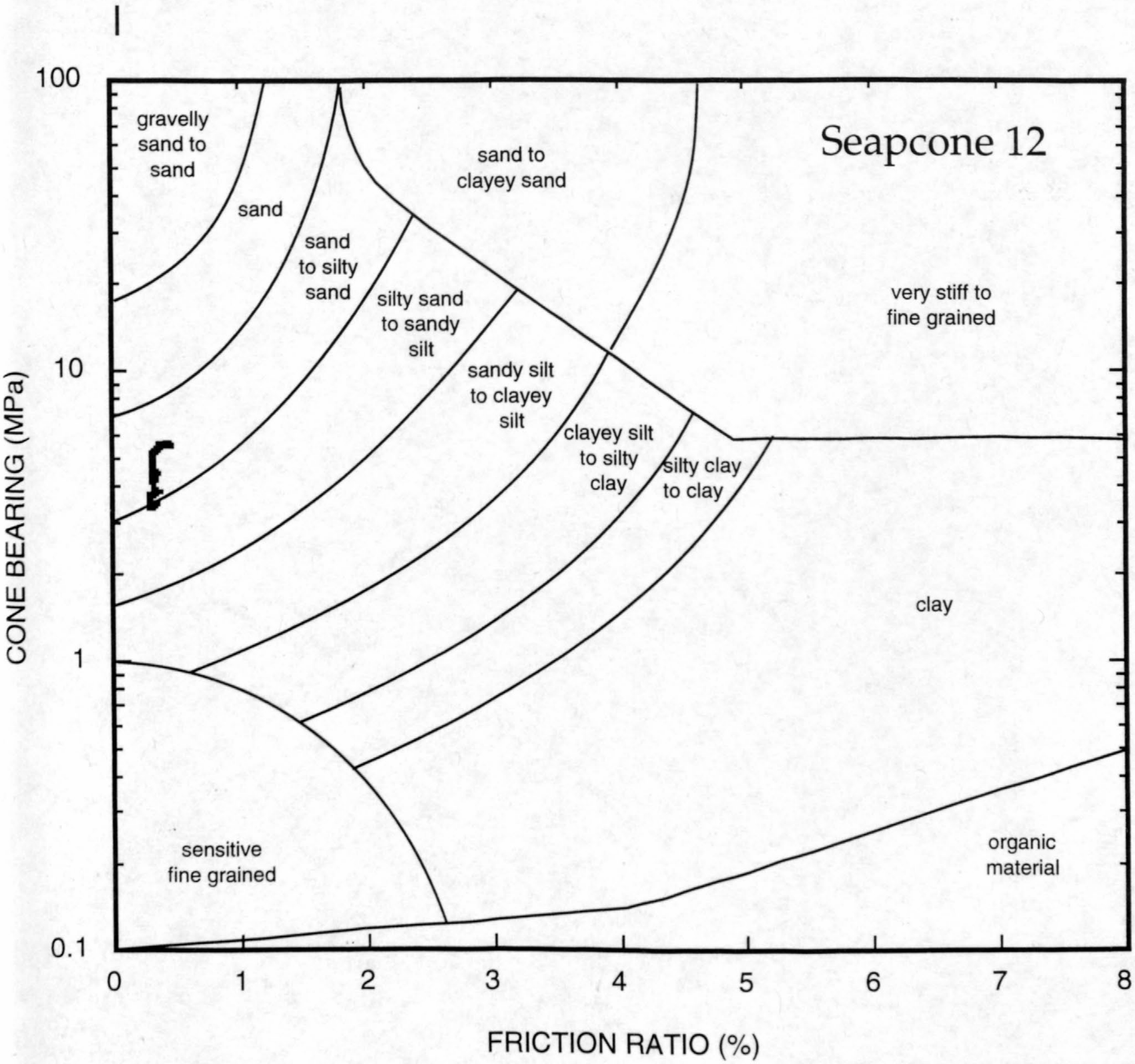

Seapcone 12
100
10
1
0.1
CONE BEARING (MPa)
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)
gravelly sand to sand
sand
sand to silty sand
sand to clayey sand
silty sand to sandy silt
sandy silt to clayey silt
clayey silt to silty clay
silty clay to clay
very stiff to fine grained
clay
sensitive fine grained
organic material

Fig. 7: Summary of sediment classification plots grouped by water depth. The indication of a decrease in grain size in the offshore direction is supported by textural analyses of diver core samples.

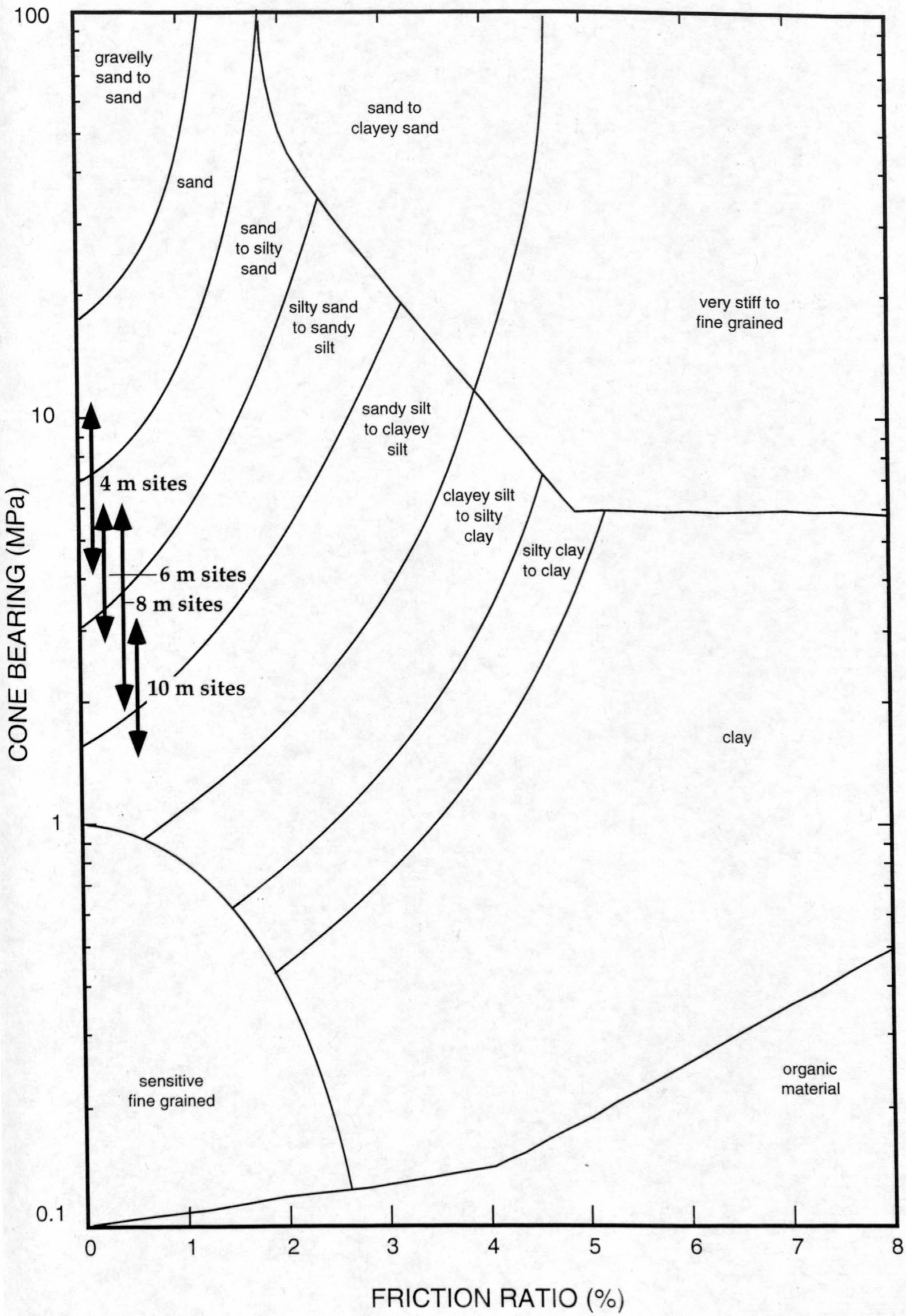
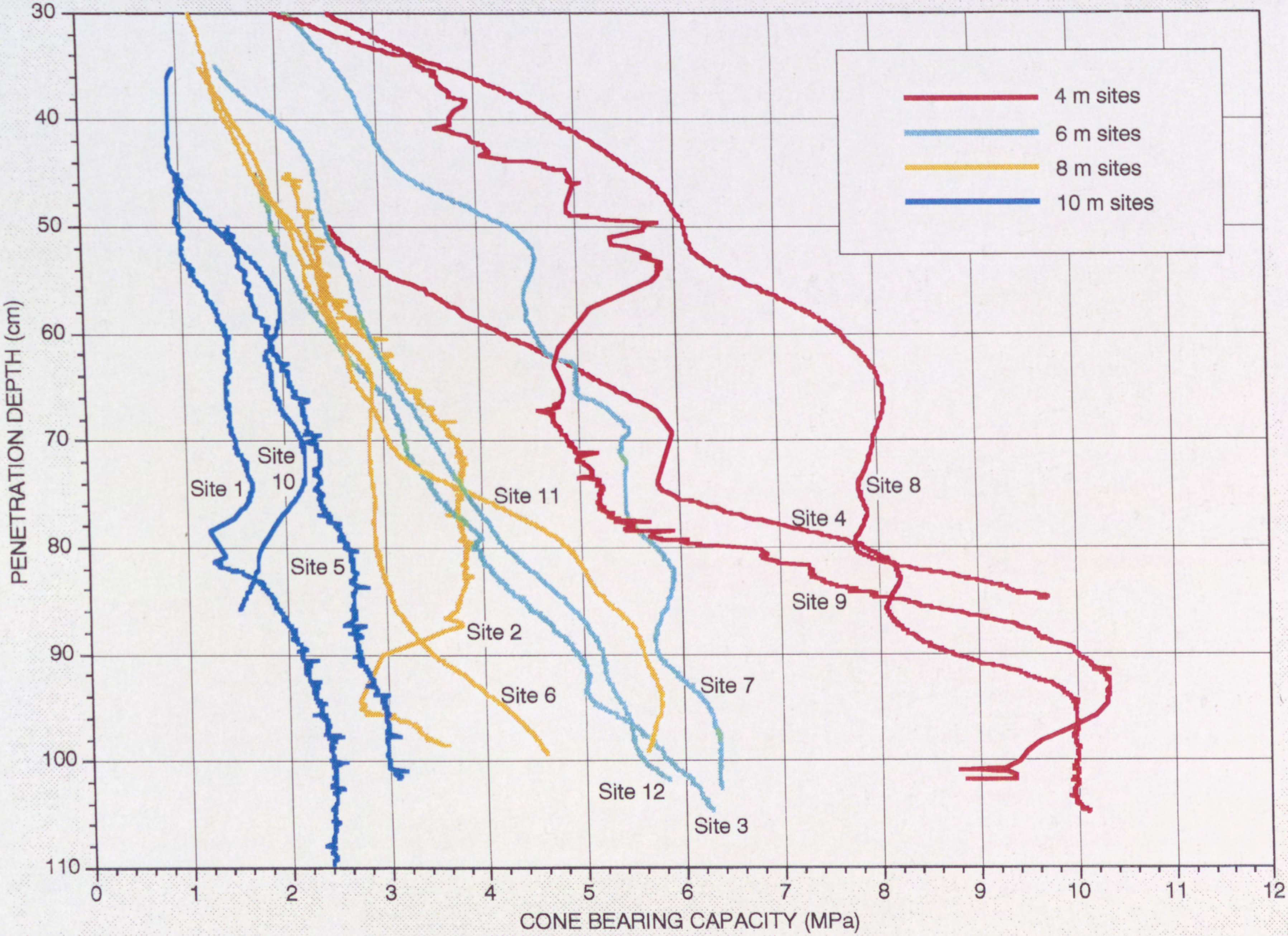
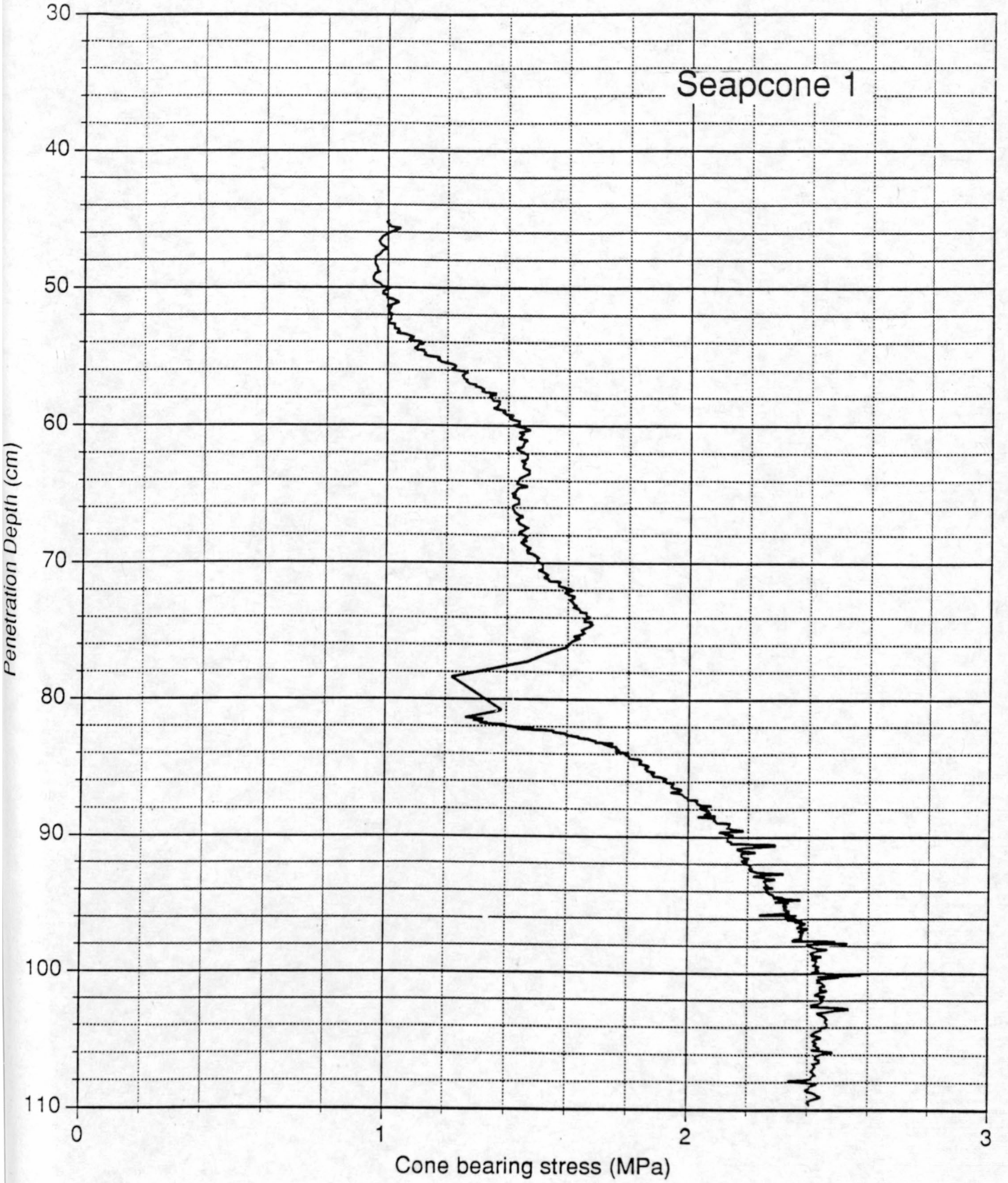

100
10
1
0.1
CONE BEARING (MPa)
0
1
2
3
4
5
6
7
8
FRICTION RATIO (%)
gravelly
sand to
sand
sand
sand to
clayey sand
sand
to silty
sand
silty sand
to sandy
silt
very stiff to
fine grained
sandy silt
to clayey
silt
clayey silt
to silty
clay
silty clay
to clay
clay
sensitive
fine grained
organic
material
4 m sites
6 m sites
8 m sites
10 m sites

Fig. 8: Composite plot of cone bearing vs penetration depth. Data cluster on the basis of water depth and the clustering generally improves with penetration depth.

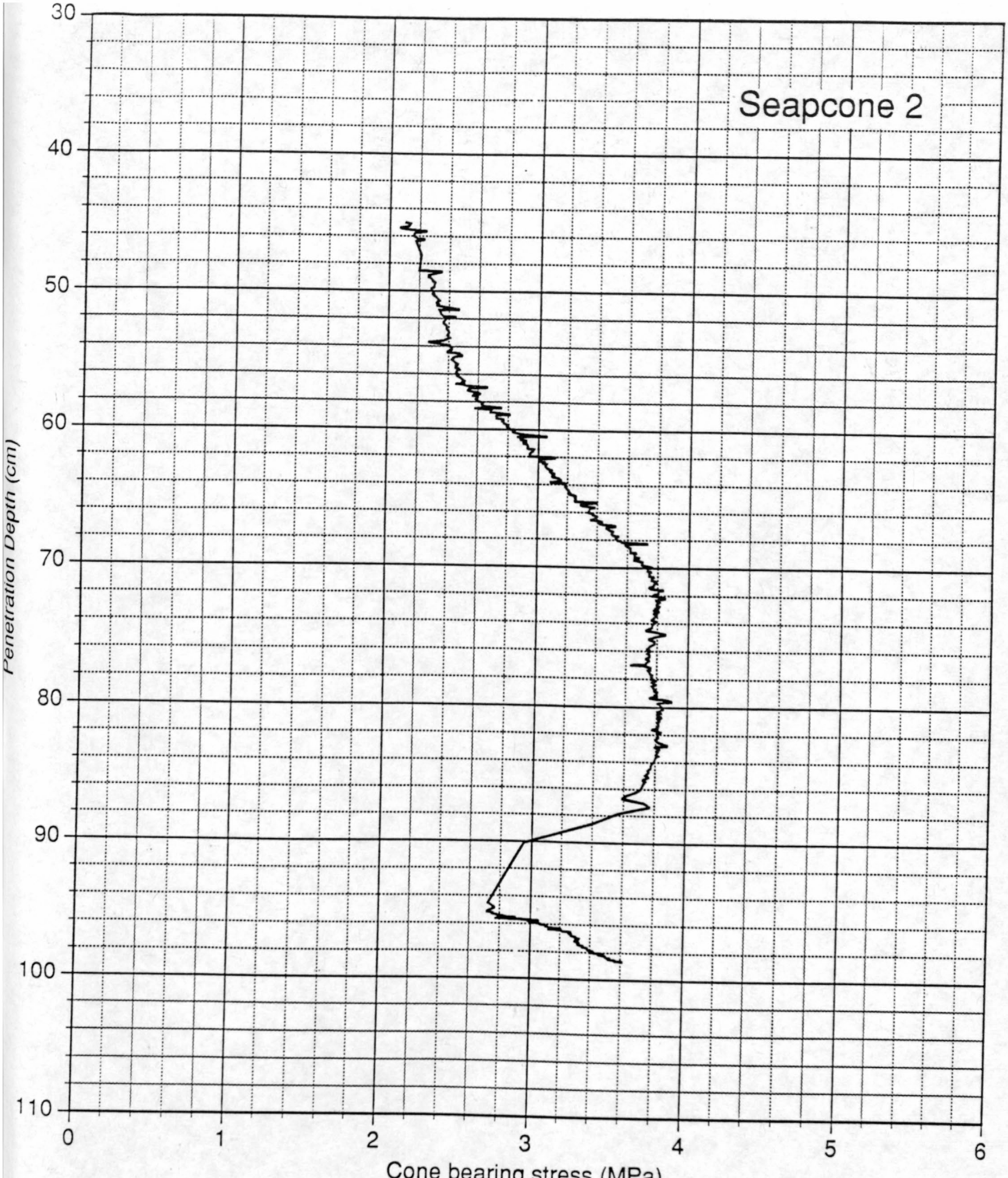

4 m sites
6 m sites
8 m sites
10 m sites
PENETRATION DEPTH (cm)
CONE BEARING CAPACITY (MPa)
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
7
8
9
10
11
12
Site 1
Site 10
Site 5
Site 11
Site 2
Site 6
Site 12
Site 3
Site 7
Site 8
Site 4
Site 9

APPENDIX A

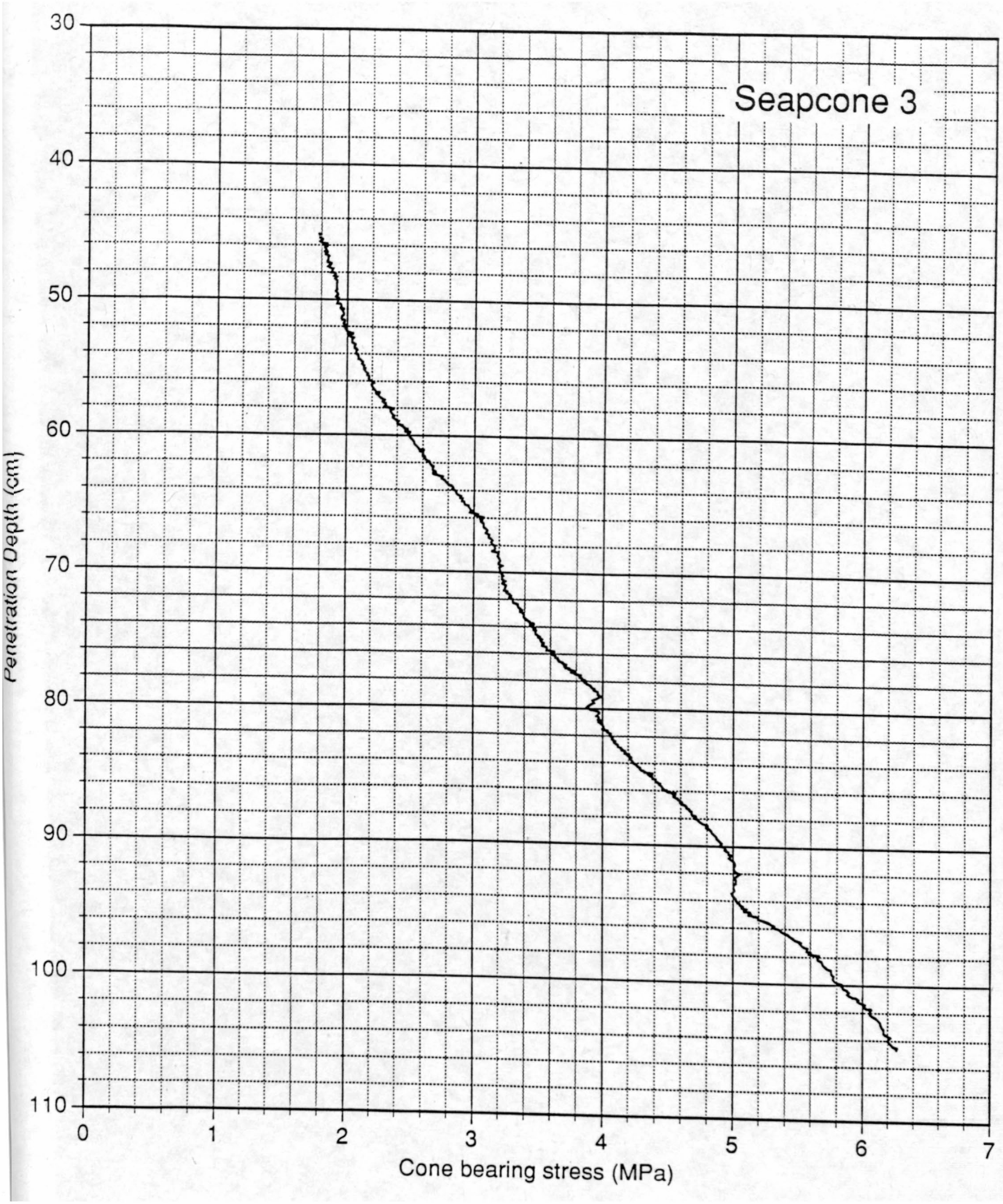
Cone bearing profiles for individual sites

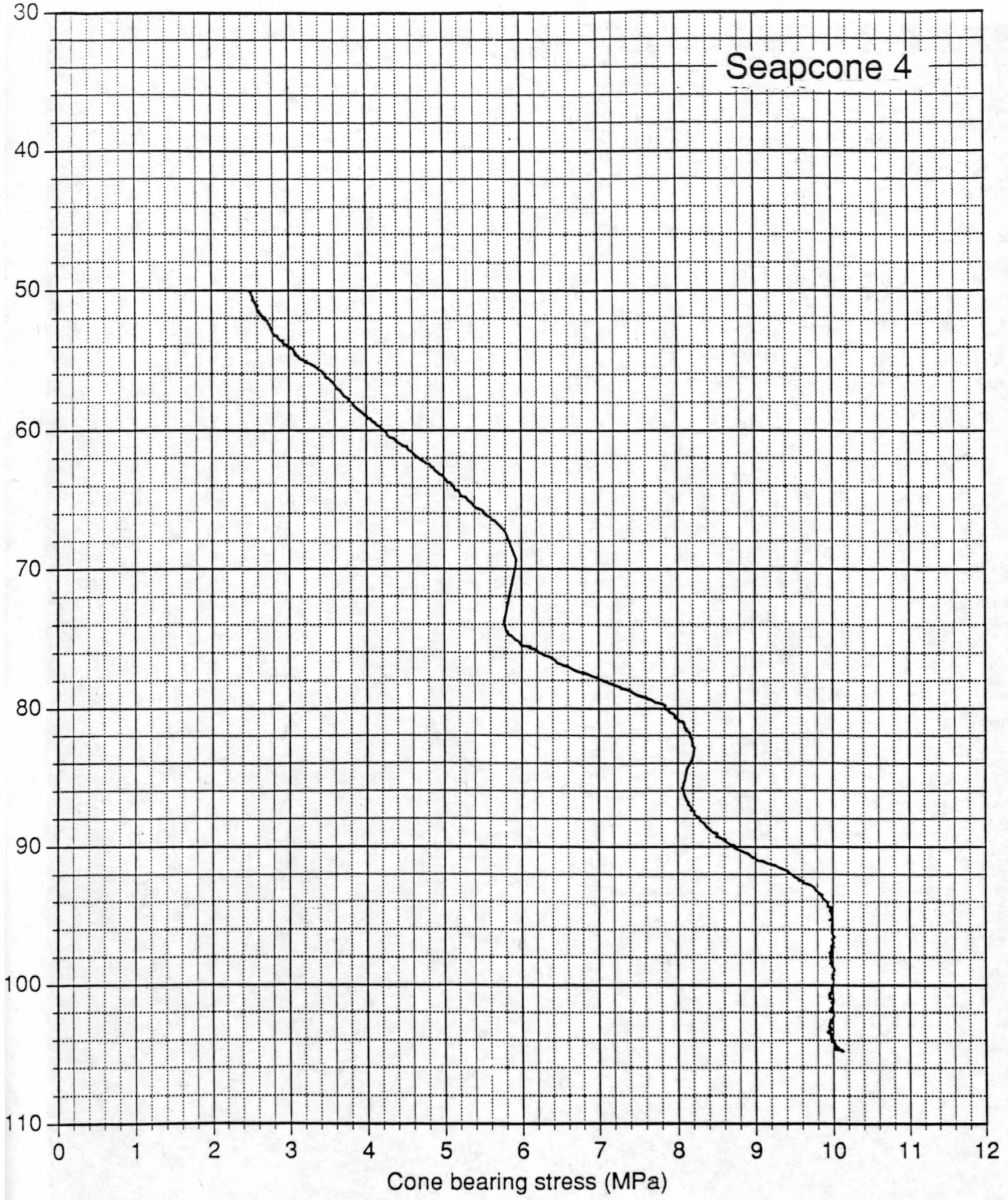


Seapcone 1
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
Cone bearing stress (MPa)

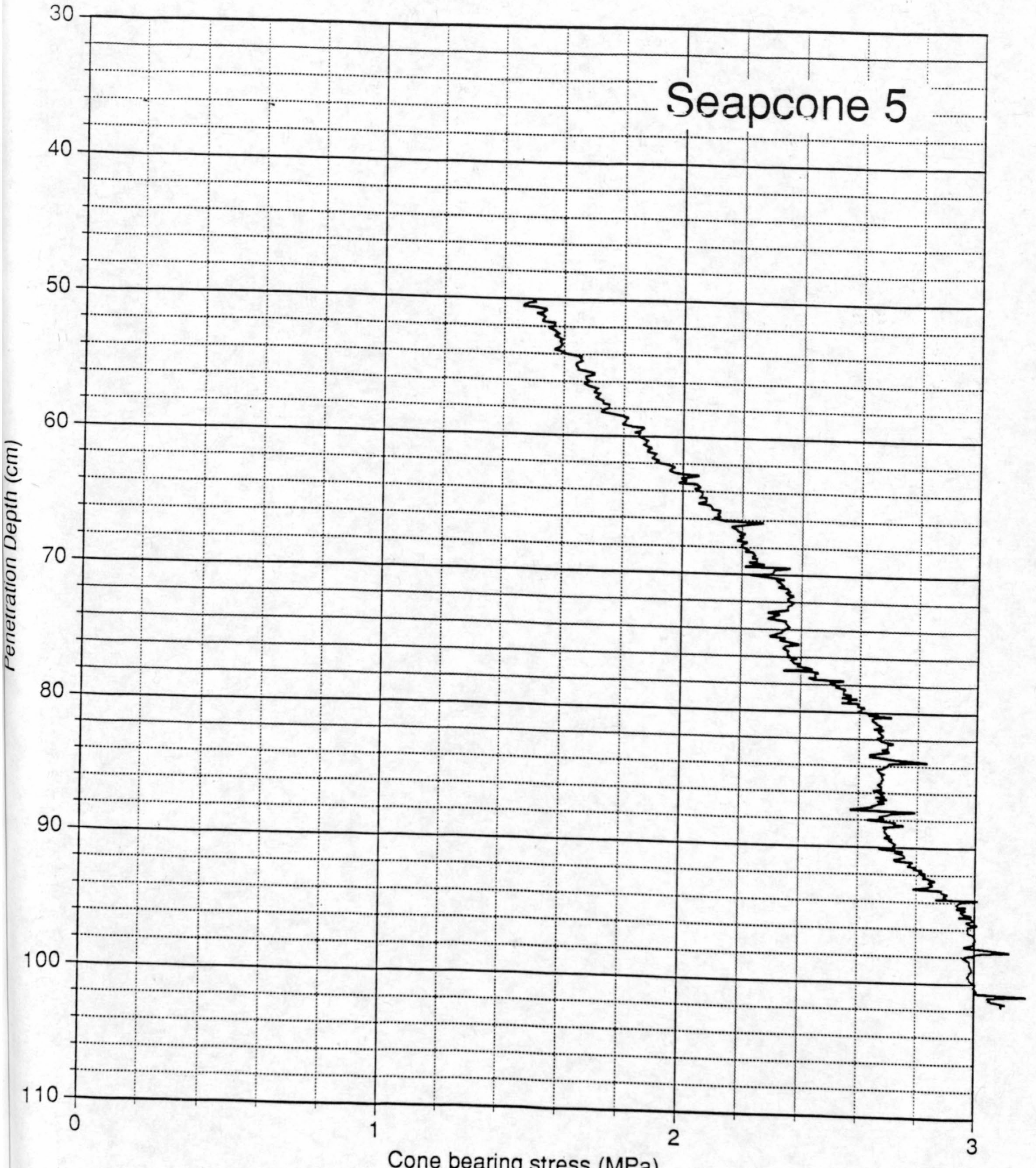


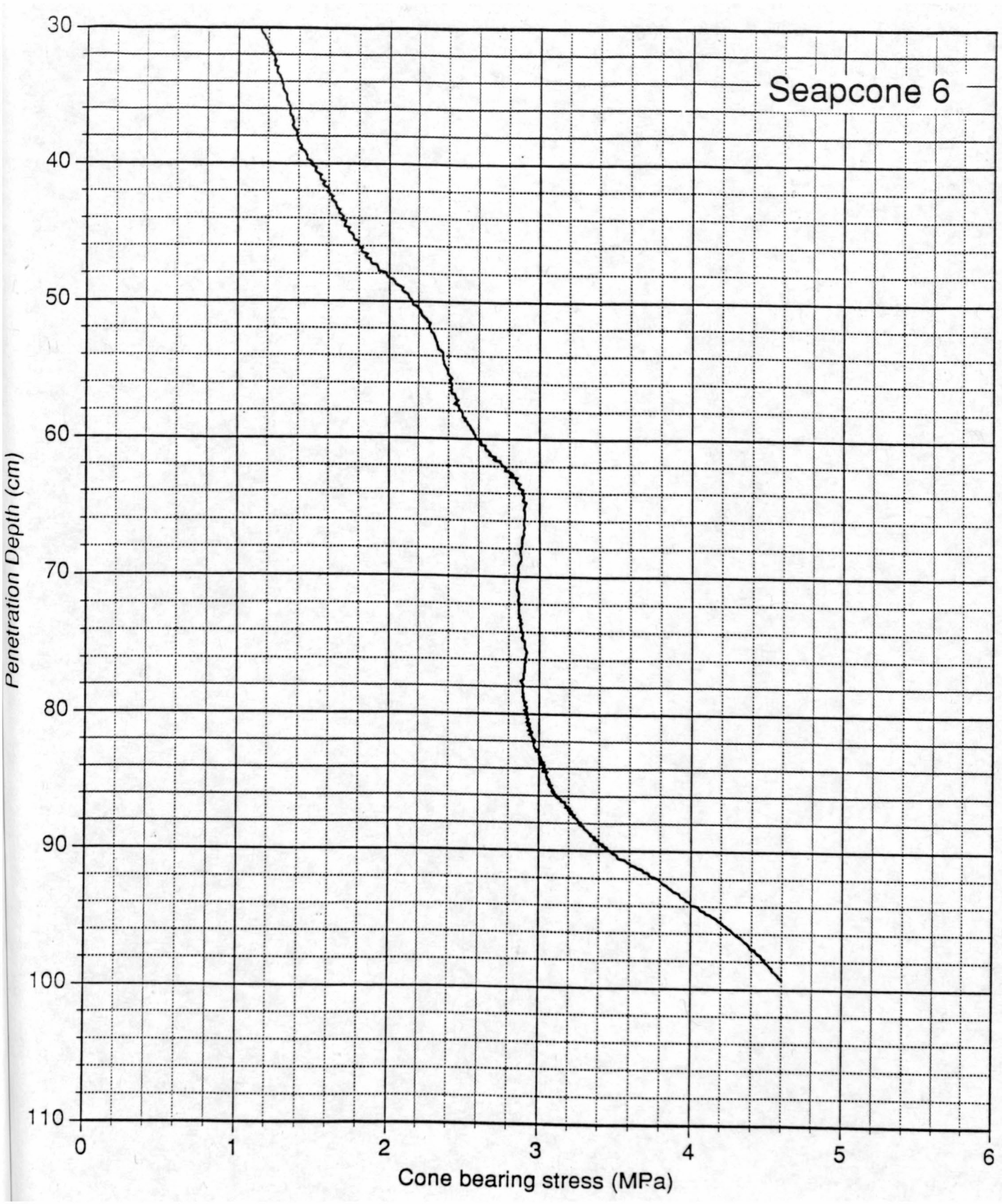
Seapcone 2
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
Cone bearing stress (MPa)

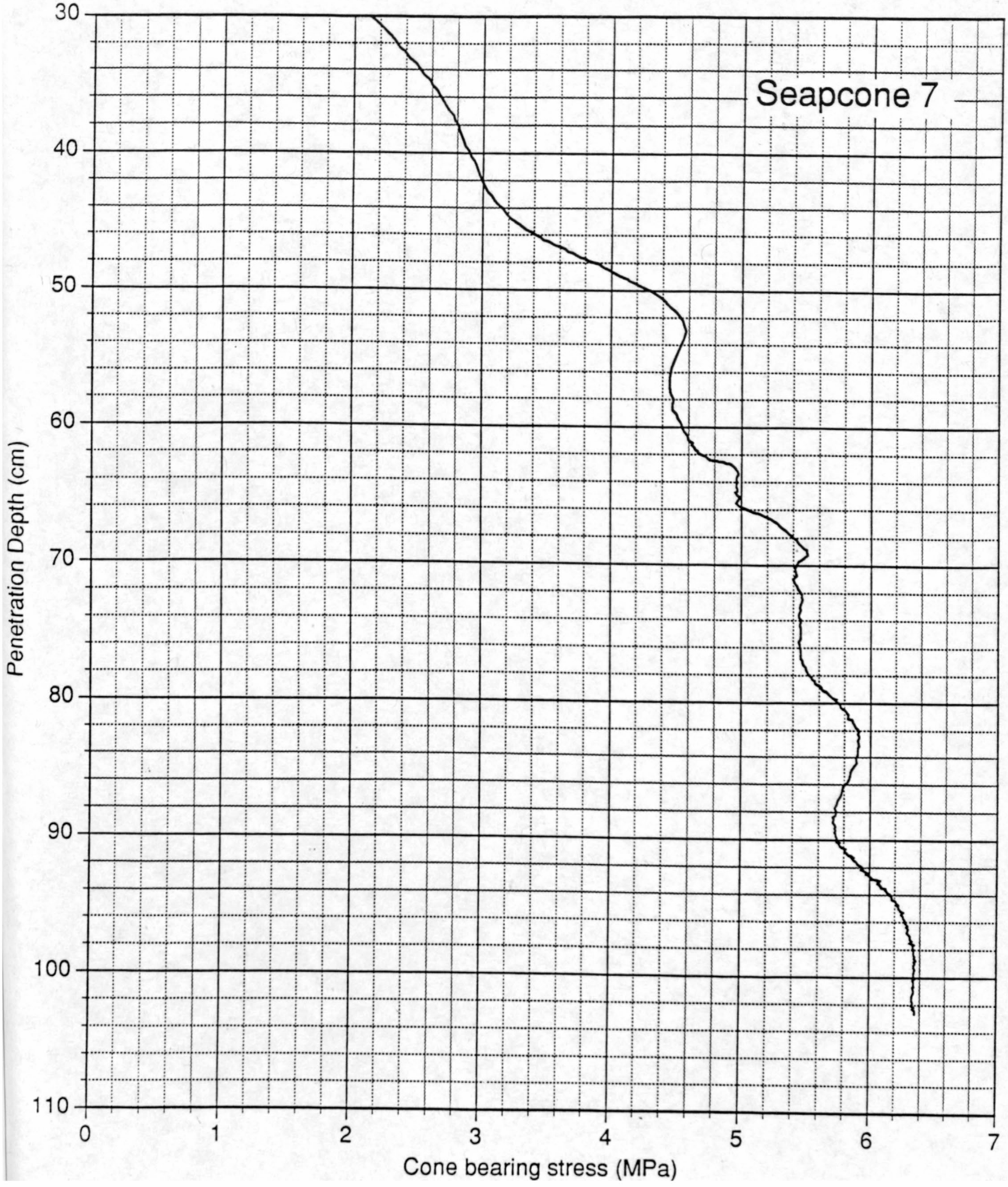

Seapcone 3
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
7
Cone bearing stress (MPa)



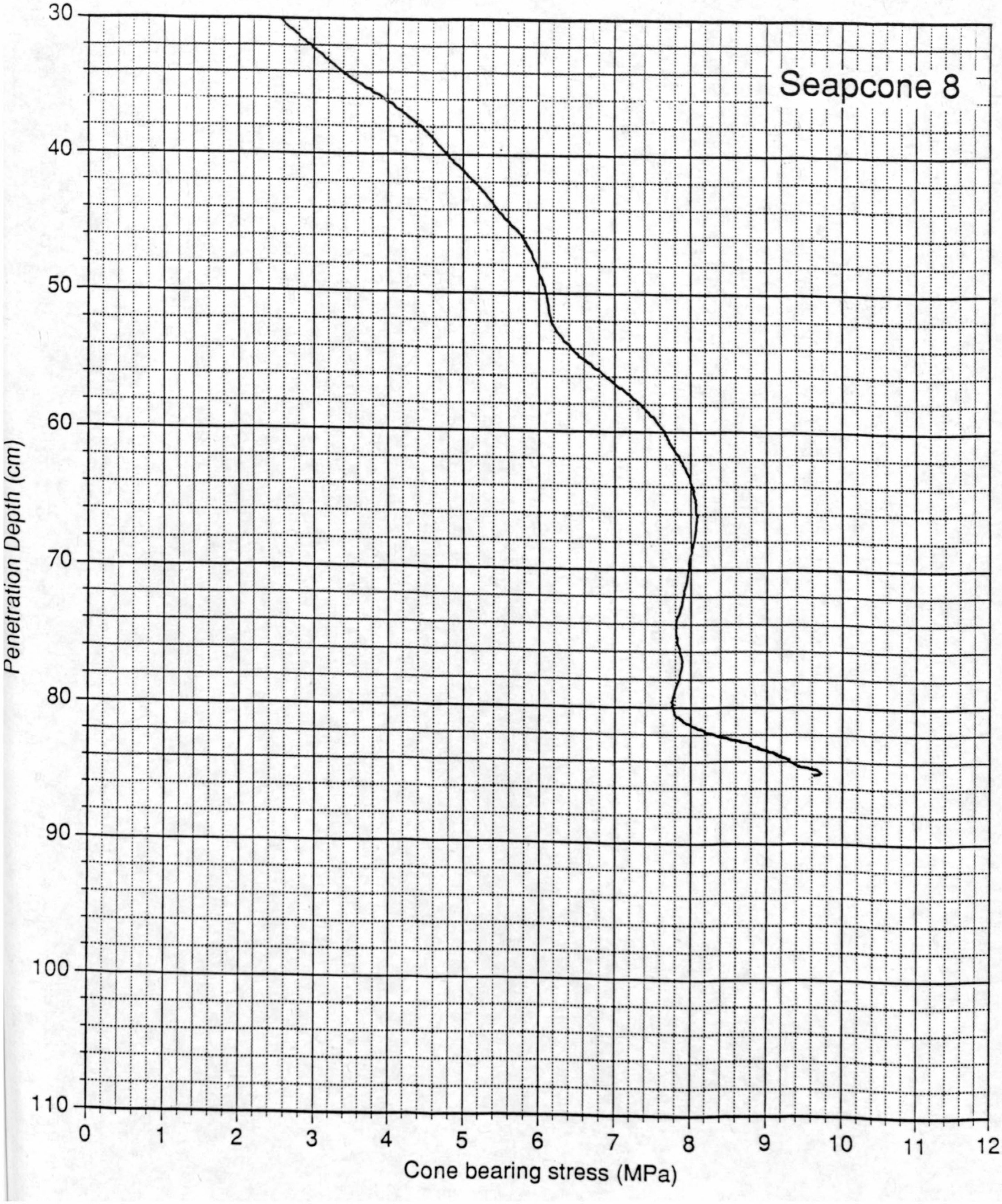
Seapcone 4
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
7
8
9
10
11
12
Cone bearing stress (MPa)


Seapcone 5
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
Cone bearing stress (MPa)

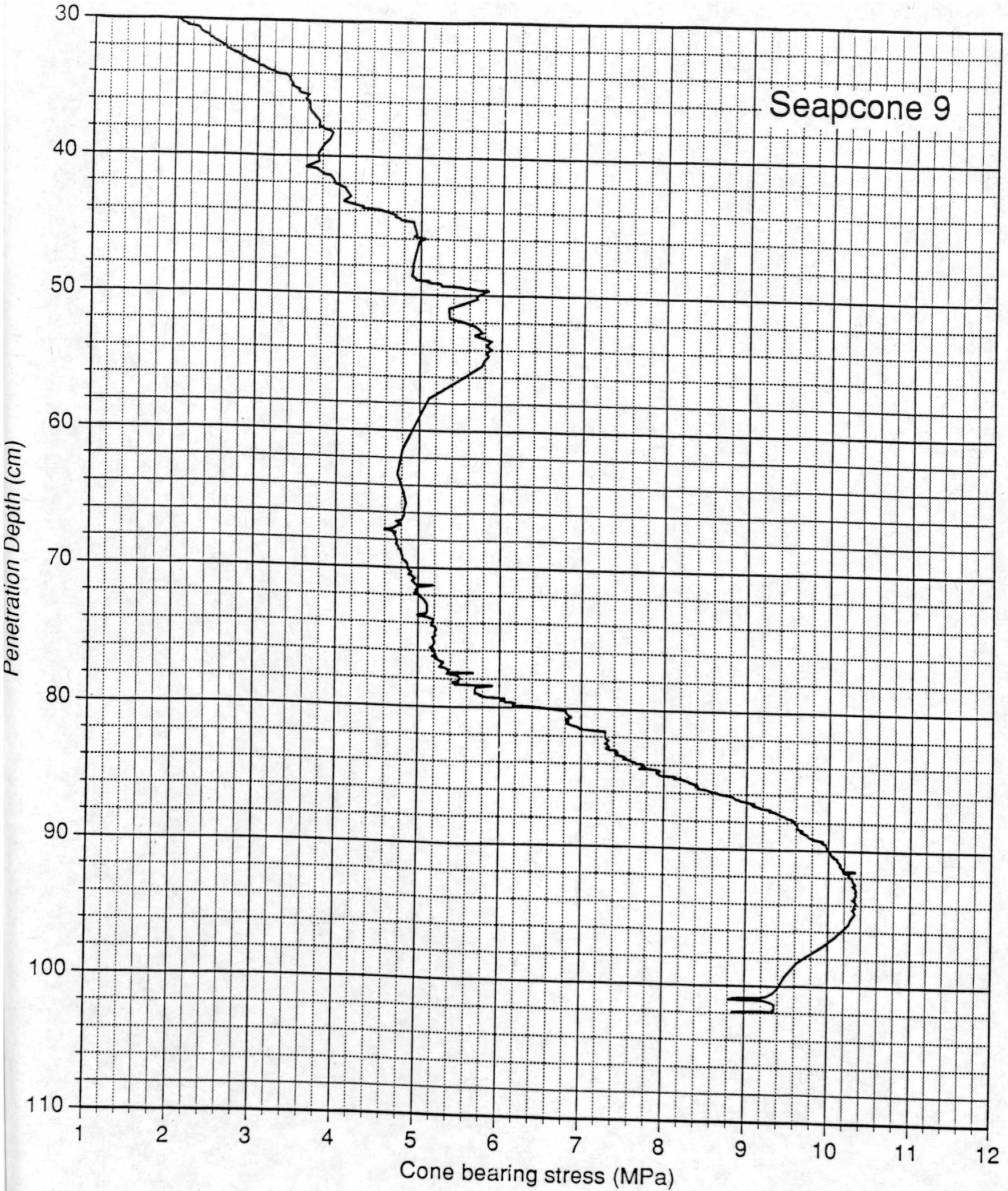

Seapcone 6
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
Cone bearing stress (MPa)

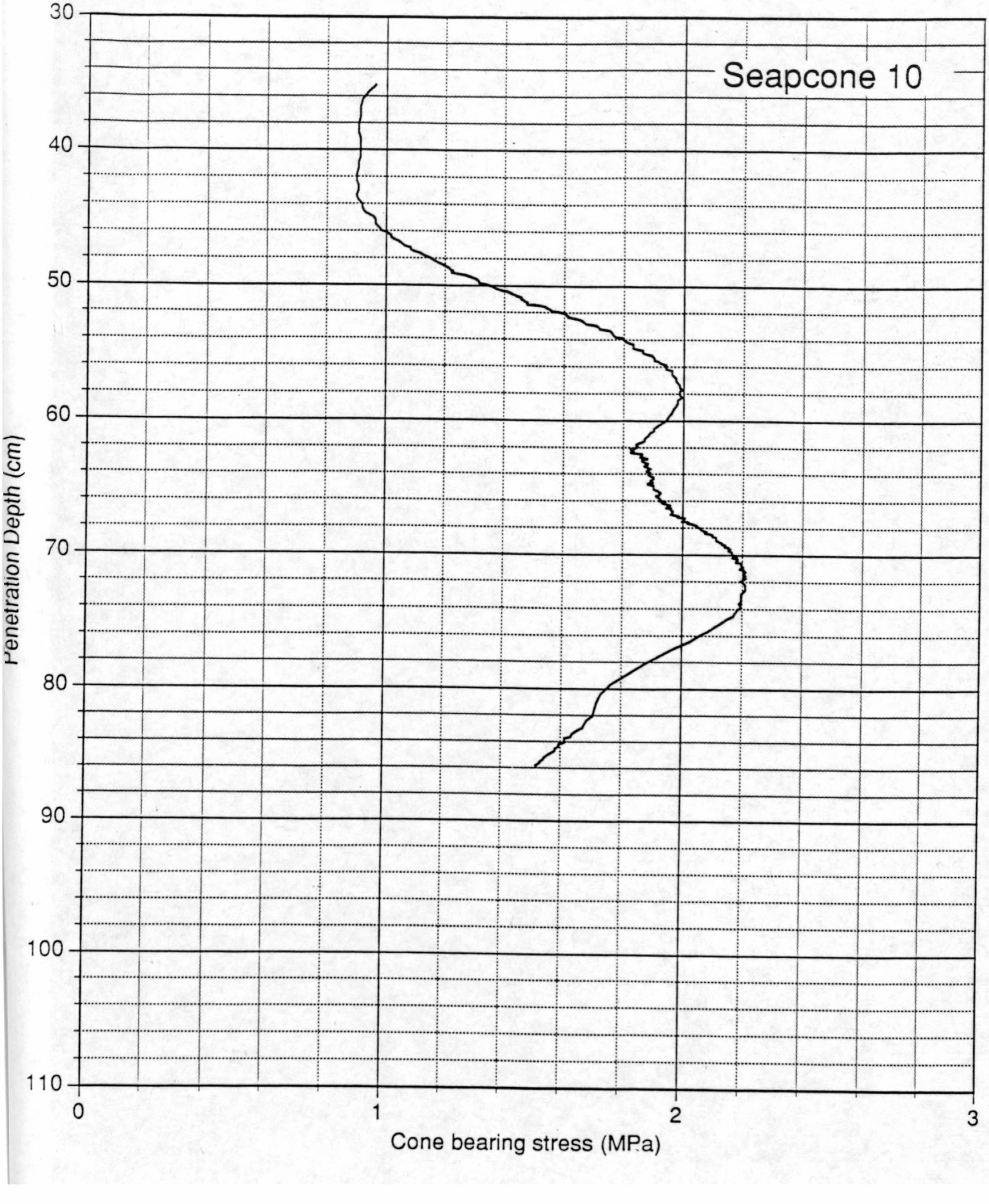


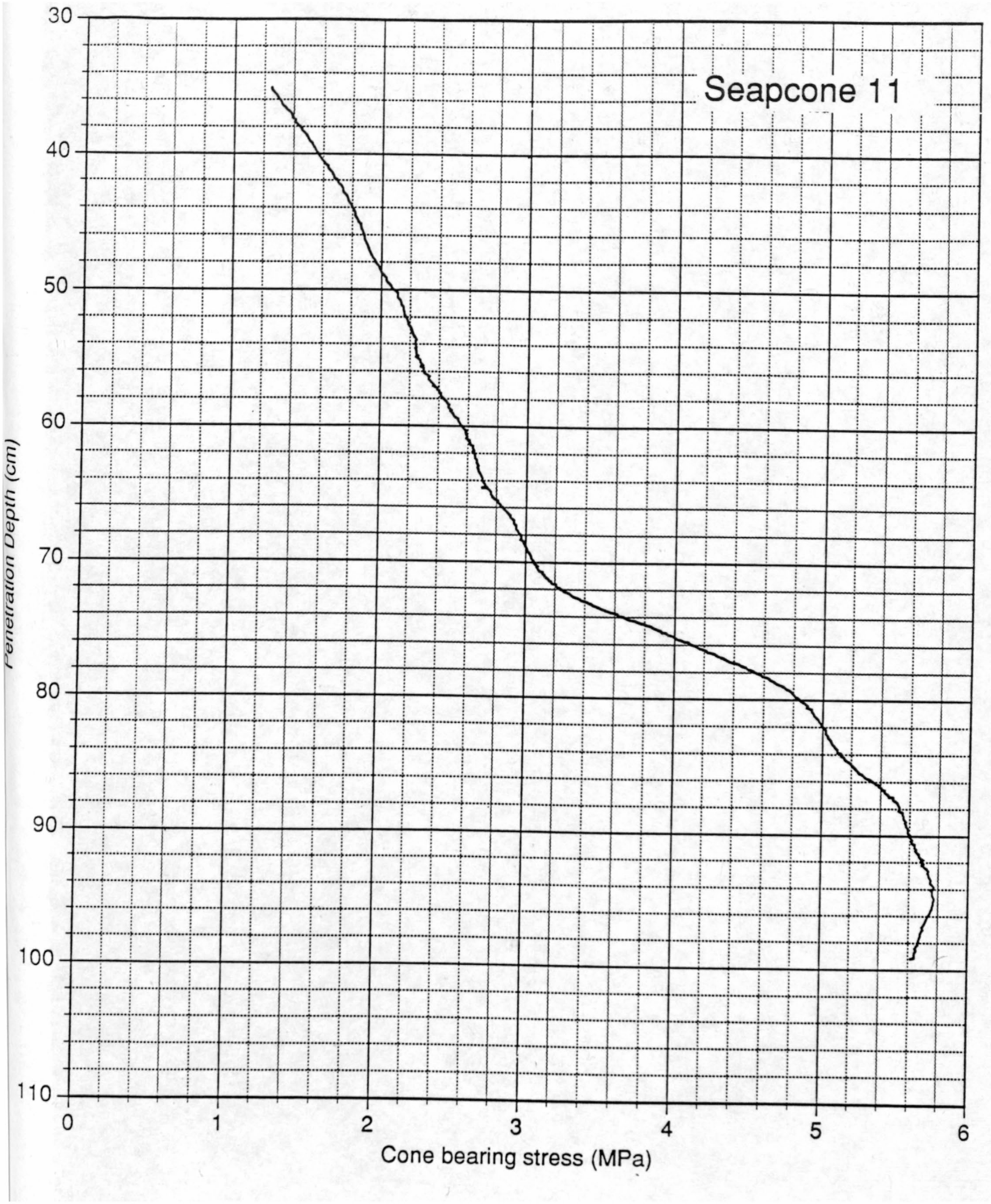
Seapcone 7
30
40
50
60
70
80
90
100
110
Penetration Depth (cm)
0
1
2
3
4
5
6
7
Cone bearing stress (MPa)



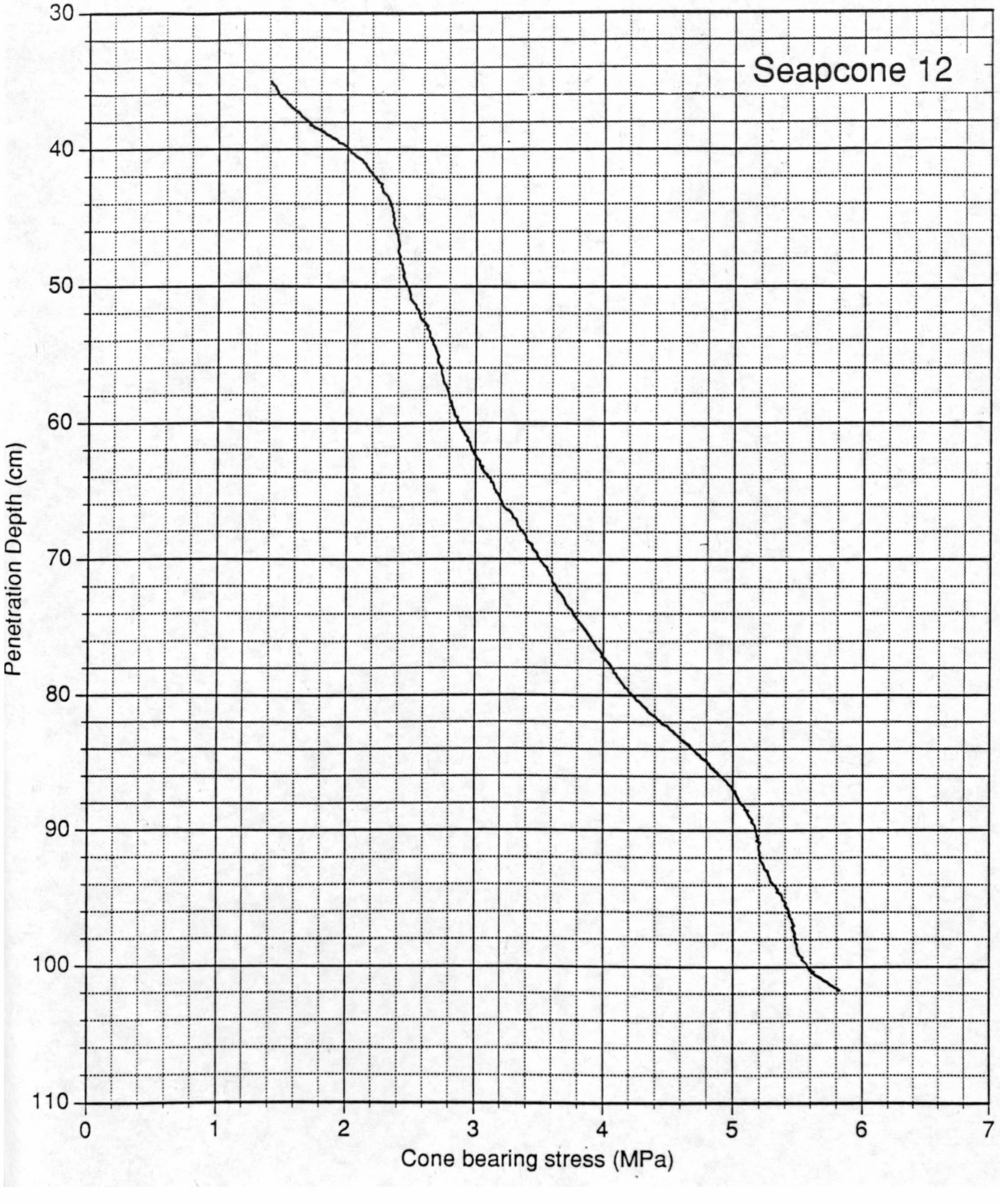
Seapcone 8
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
7
8
9
10
11
12
Cone bearing stress (MPa)


Seapcone 9
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
1
2
3
4
5
6
7
8
9
10
11
12
Cone bearing stress (MPa)


Seapcone 10
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
Cone bearing stress (MPa)



Seapcone 11
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
Cone bearing stress (MPa)



Seapcone 12
Penetration Depth (cm)
30
40
50
60
70
80
90
100
110
0
1
2
3
4
5
6
7
Cone bearing stress (MPa)