



NRL/MR/7420--14-9559

Investigation of Sediment Strength Characteristics in Approaches to Boston Harbor Using STING Penetrometer

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September 17, 2014

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 17-09-2014		2. REPORT TYPE Memorandum Report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Investigation of Sediment Strength Characteristics in Approaches to Boston Harbor Using STING Penetrometer				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Andrei Abelev				5d. PROJECT NUMBER 74-6717-A4	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory, Code 7420 4555 Overlook Avenue, SW Washington, DC 20375-5320				8. PERFORMING ORGANIZATION REPORT NUMBER NRL/MR/7420--14-9559	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Research Laboratory, Code 7420 4555 Overlook Avenue, SW Washington, DC 20375-5320				10. SPONSOR / MONITOR'S ACRONYM(S) NRL	
				11. SPONSOR / MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This report discusses results of two series of STING penetrometer measurements of seafloor sediment strength in areas of Boston Harbor approach. The experimental data is analyzed and used in sediment characterization and sediment strength predictions.					
15. SUBJECT TERMS Seafloor strength STING Impact burial					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited	58	Andrei Abelev (202) 404-1107

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Introduction and study location

This report discusses two series of measurements of sediment bearing strength, conducted in Box 3.1nm and in Box5 – both on approach to Boston Harbor - during 01/2014 and 04/2014 trips on board Matthew Hughes (BHC). The results presented and the discussion that follows also include data from a previous trip, conducted in 12/2013 and reported earlier (*Abelev, 2014*).

The areas of sediment strength exploration included Box 3.1nmi (Fig. 1) and Box 5 (Fig. 2). Both were 1x1 nm in size. Each of the two figures includes outlines of a study box, a portion of a nautical chart, all stations where the STING measurements were performed (with station IDs), and overlays from the bottom sediment database (NAVOCEANO). Information included on the nautical chart in Box 3.1 indicates a presence of two wrecks, whereas Box 5 contains one, with only an approximate knowledge of the position. Another notable feature located just North of Box 5, is the dumping ground of dredged material. Dredged material may contain many sediment classes, typically including clay, silt, and sand, and may therefore have pronounced effects on the STING measurements; these are further discussed below. As can be seen in Fig. 2, STING measurements in Box 5 were conducted not only within the designated box limits, but also extended beyond its boundaries by approximately 500m on those sides of the box that allowed this extension. Limitations included a line of anchors to NNW of Box 5, connected to the feature, labeled “Obstruction Submerged Buoy”, and the nature reserve boundary, where operations are prohibited, on the East side of the box.

The main objective in investigating these two specific locations was to find and characterize the bottom sediments that may have the lowest bearing capacity (sediment shear strength), as guided by the available sediment maps. The bulk of Box 3.1 area includes sediment labeled as Terrigenous Fine Silt, with the SE corner extending into an area of Terrigenous Silt sediment type. The survey area of Box 5 attempts to include the bulk of bottom sediments identified as Terrigenous Clay, within the limits imposed by the various obstructions and prohibited areas. Immediately adjacent to this clayey sediment is the area marked as Terrigenous Very Fine Silt. Both of these sediment types, as they appear on the available sediment map, suggest the softest conditions of the entire Boston Harbor approach area.

The coordinates of **Box 3.1**nmi were as follows:

Field	Latitude	Longitude
NW Corner	42°25.000'N	070°39.500'W
NE Corner	42°25.000'N	070°38.150'W
SE Corner	42°24.000'N	070°38.150'W
SW Corner	42°24.000'N	070°39.500'W

The coordinates of **Box 5** were as follows:

Field	Latitude	Longitude
NW Corner	42°23.475'N	70°34.520'W
NE Corner	42°23.700'N	70°33.200'W
SE Corner	42°22.725'N	70°32.895'W
SW Corner	42°22.500'N	70°34.215'W

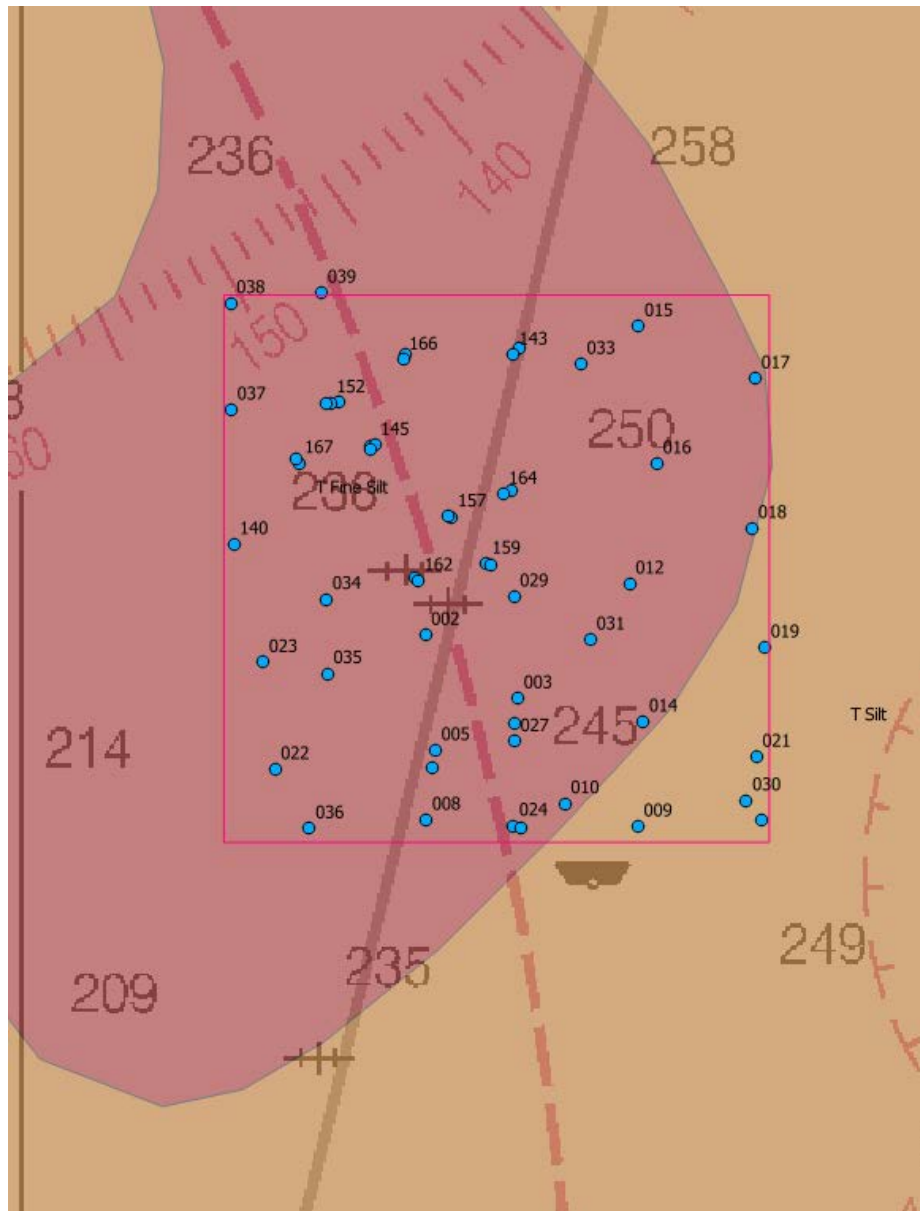


Fig. 1 Box 3.1nmi study area (red outline); STING deployments (in blue with station numbers), nautical chart overlay and NAVOCEANO sediment map overlay – majority of Box 3.1nmi is in Terrigenous Fine Silt (purple), South-East corner is in Terrigenous Silt (brown)

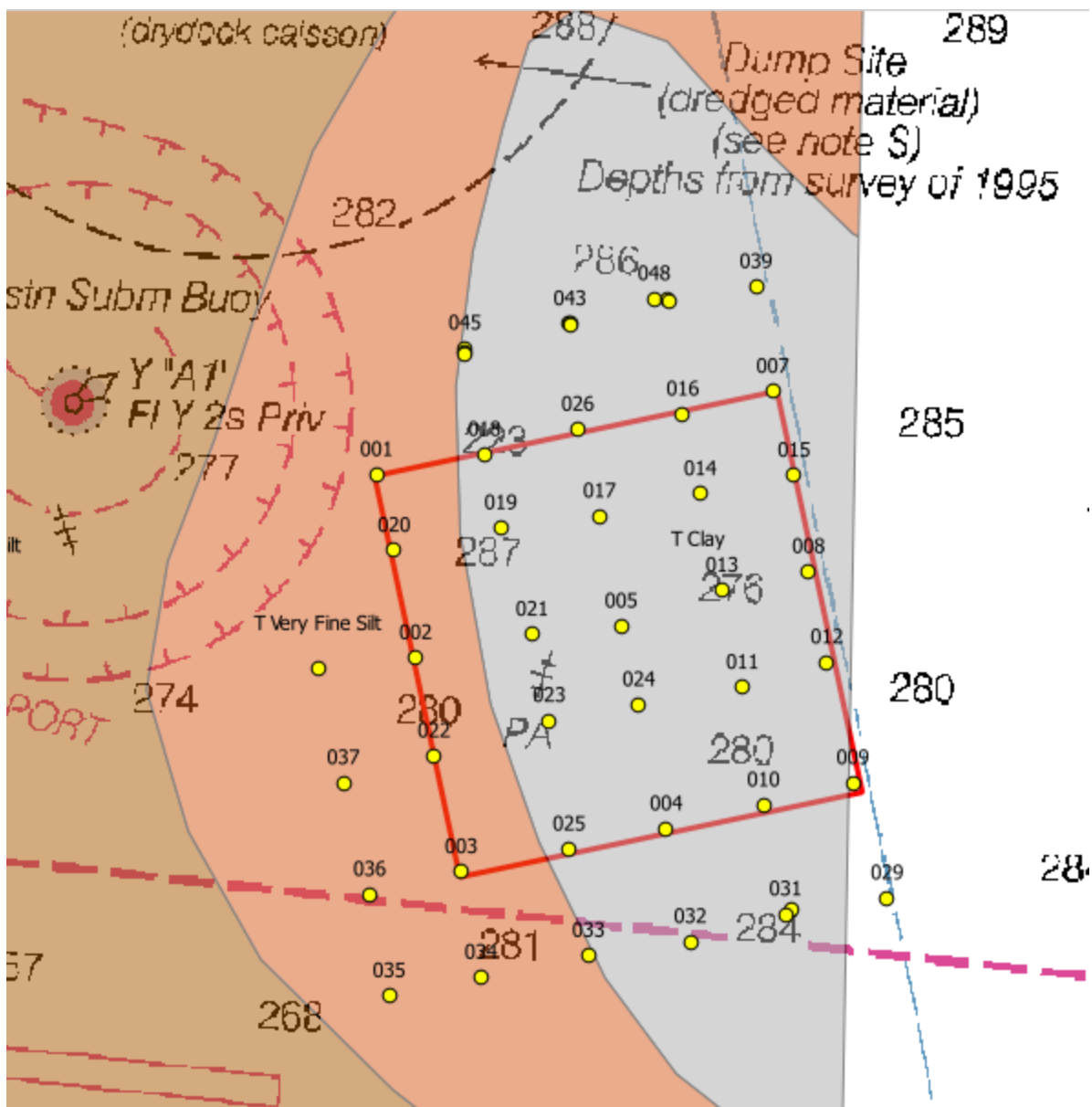


Fig. 2 Box5 study area (red outline), STING positions (in yellow, with drop numbers), Nautical chart overlay, NAVOCEANO sediment map overlay – most of Box 5 is in Terrigenous Clay (gray), West margin is in Terrigenous Very Fine Silt (light brown)

Instrumentation

A set of three 7420 STINGs (Sea Terminal Impact Naval Gradiometer - *Jasco Research Ltd.*, 2002) was used in conducting sediment analysis for bearing strength. These probes consist of a fin-stabilized main body with extension/penetrator rods attached to it (Fig. 3a). Several diameter foot-plates can be attached to the bottom (penetrating) end of these extension rods, including 25, 35, 50, and 70mm diameter. The main body of the probe (Fig. 3b) includes a single axis accelerometer, water pressure transducer, and data acquisition and storage unit with the total on-board memory sufficient for 4.5 min data acquisition, when recording in dual-channel mode (acceleration and water pressure). During this time interval, repeated drops of the penetrometer are conducted at each station to provide for averaging necessary in naturally heterogeneous seafloor sediment conditions. Normally, three to four drops per location were performed.

Selection of the STING foot diameter may be guided by several considerations, including intended depth of penetration where the smaller the foot diameter, the greater is the resulting penetration burial thus maximizing the depth surveyed with the probe; the quality of data used in correlations with the sediment undrained shear strength, as some diameters may yield better modeling outcomes due to a variety of soil plastic flow effects around the penetrometer foot; or direct empirical relations between the maximum depth of the penetrating probe with expected depth of burial of larger objects. These size effects were studied with several penetrometers of varying dimensions (*Mulhearn*, 2002) and showed that little change in *maximum burial* occurs for circular bodies of diameter greater than 70 mm. During this survey, a 75mm foot was utilized, to utilize the benefits of these direct correlations.

In general, the numerical model used in retrieving the sediment strength from deceleration records of probes is applicable to cohesive materials (clays and silts) or mixtures that exhibit a mostly cohesive behavior. If thick enough layers of sandy material are present, they result in

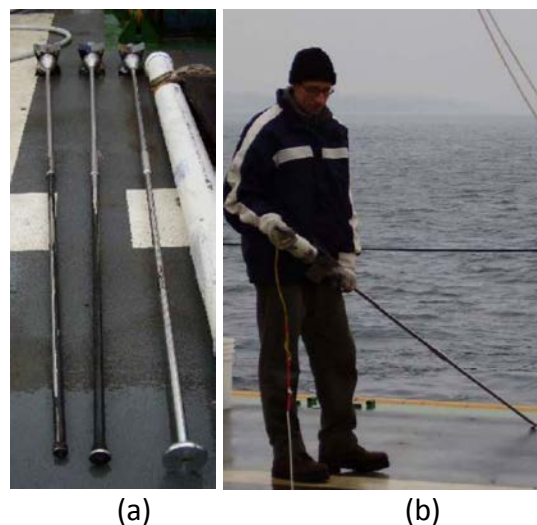


Fig. 3 (a) STING with 2m rods and several different foot sizes attached (25mm – left, 35mm – middle, 70mm – right); (b) STING before deployment with tail cone and tether attached

characteristic spikes in acceleration (and thus the derived bearing strength) records, due to the dilative effects in the sandy material matrix. These layers need not be clean sand to impose this effect and are most likely a mixture with surrounding finer-grained material (silt and clay). These dilative effects, however, may severely impede penetration of various objects, especially when the impact velocities are high (*e.g.* greater than 1 meter per second) relative to the overall sediment permeability or the ability to dissipate excess pore water pressures quickly. For further information on the effects of dilation on dynamic penetration, the reader is referred to *Stoll et al.*, 2007.

The range of the accelerometer used in the STINGs is chosen in such a way as to maximize resolution in investigating mostly cohesive/clayey soils. When significantly higher resistance is encountered in sandy layers, the accelerometer often saturates, exceeding the range. Part of the calculation may still be conducted, retrieving the pseudo-strength values, but these should be treated with care, as they lay outside the normal range of the sediment strength retrieval model.

Such series of spikes (leading to accelerometer saturation) were encountered in both study boxes (Figs. 4 and 5) and are especially numerous in Box 3.1. In Box 5, these effects were observed at only one station (#18). These figures (4 and 5) show the variation of the calculated shear strength with sediment depth and include all individual STING drops. These plots are useful in identifying the overall spectrum of material encountered at each location, the spread in the data and possible similarities between drops and stations.

Results: STING penetration and shear strength

The results of the STING deployments are summarized in Table 1 for Box 5 and Table 2 for Box 3.1. Each station includes an average of typically three STING drops. Maximum penetration values are shown and include the average and the standard deviation values of all the drops performed at each station.

Examination of the burial data from Box 5 shows relatively deep penetrations, indicating soft sediment strength, with the exception of one – Station # 18, also highlighted in the table and also labeled in Fig. 5. Additionally, whereas the water depth at all locations was relatively uniform of around 91m, this one station (#18) was much shallower, at only at 81m of water depth, representing a mound that is almost 10m above the adjacent seafloor. The overall penetration burial of the probe at this station is very small – only 18cm on average. The calculated bearing strength profiles for each of the three drops at this location (Station 18, Box 5) are shown in Fig. 6, demonstrating a response of a typical dilative sandy layer that begins very close to the sediment-water interface (perhaps at 3cm mark). This location may be a result of dumping of dredged material that nominally (according to the nautical chart) should only be found about 1km north of this station.

Table 1 STING deployment list, 03/2014 trials, Box 5, Boston Harbor approach

Station number	Lat, deg	Lon, deg	Date, EST	Water depth, m	Average Penetration depth, m	STDEV depth, m
1	42.3913	-70.57523	3/5/2014	92	0.65	0.06
2	42.38388	-70.5729	3/5/2014	90	0.70	0.01
3	42.37521	-70.57018	3/5/2014	90	0.70	0.04
4	42.37711	-70.55897	3/5/2014	91	0.64	0.03
5	42.38532	-70.56165	3/5/2014	91	0.70	0.07
7	42.39498	-70.55357	3/5/2014	92	0.76	0.07
8	42.38768	-70.55142	3/5/2014	91	0.81	0.05
9	42.37912	-70.54878	3/5/2014	91	0.84	0.01
10	42.37815	-70.55366	3/5/2014	92	0.75	0.02
11	42.38292	-70.55493	3/5/2014	90	0.81	0.03
12	42.38401	-70.55032	3/5/2014	91	0.67	0.02
13	42.38685	-70.55615	3/5/2014	90	0.69	0.02
14	42.39076	-70.55744	3/5/2014	91	0.75	0.07
15	42.39158	-70.55231	3/5/2014	92	0.69	0.03
16	42.39399	-70.55848	3/5/2014	93	0.67	0.01
17	42.38978	-70.56295	3/5/2014	93	0.70	0.03
18	42.3922	-70.56933	3/5/2014	81	0.14	0.07
19	42.38923	-70.56836	3/5/2014	94	0.67	0.02
20	42.38823	-70.57419	3/5/2014	92	0.75	0.11
21	42.38492	-70.56653	3/5/2014	92	0.81	0.10
22	42.3799	-70.57179	3/5/2014	91	0.69	0.03
23	42.38143	-70.5655	3/5/2014	92	0.74	0.04
24	42.38214	-70.5606	3/5/2014	92	0.74	0.03
25	42.37621	-70.56428	3/5/2014	92	0.76	0.05
26	42.39329	-70.56423	3/5/2014	94	0.78	0.04
29	42.37446	-70.54678	3/5/2014	90	0.73	0.02
30	42.37393	-70.55204	3/5/2014	90	0.66	0.06
32	42.37254	-70.55754	3/5/2014	90	0.62	0.02
33	42.3719	-70.56311	3/5/2014	89	0.66	0.04
34	42.37093	-70.56899	3/5/2014	88	0.63	0.04
35	42.37011	-70.57401	3/5/2014	87	0.67	0.02
36	42.37422	-70.57518	3/5/2014	88	0.67	0.05
37	42.37874	-70.57674	3/5/2014	89	0.61	0.05
38	42.38341	-70.57817	3/5/2014	89	0.64	0.02
39	42.39923	-70.55459	3/5/2014	92	0.76	0.04
42	42.39764	-70.56482	3/5/2014	93	0.70	0.04
45	42.39651	-70.57051	3/5/2014	93	0.63	0.03
48	42.39866	-70.56017	3/5/2014	92	0.76	0.09

Table 2 STING deployment list, 01/2014 trials, Box 3.1nmi, Boston Harbor approach¹. All water depths were approximately 74m

Station number	Lat, deg	Lon, deg	Date, EST	Average penetration depth, m	STDEV penetration depth, m
2	42.40631	-70.65003	1/29/2014	0.44	0.01
3	42.40438	-70.64621	1/29/2014	0.48	0.02
5	42.40280	-70.64961	1/29/2014	0.32	0.03
6	42.40227	-70.64975	1/29/2014	0.29	0.08
8	42.40068	-70.64999	1/29/2014	0.32	0.02
9	42.40048	-70.64126	1/29/2014	0.52	0.06
10	42.40118	-70.64427	1/29/2014	0.51	0.02
12	42.40787	-70.64160	1/29/2014	0.52	0.05
14	42.40367	-70.64104	1/29/2014	0.54	0.03
15	42.41571	-70.64123	1/29/2014	0.51	0.04
16	42.41153	-70.64047	1/29/2014	0.53	0.02
17	42.41412	-70.63641	1/29/2014	0.53	0.04
18	42.40956	-70.63654	1/29/2014	0.61	0.06
19	42.40593	-70.63602	1/29/2014	0.44	0.02
21	42.40260	-70.63637	1/29/2014	0.50	0.02
22	42.40222	-70.65623	1/29/2014	0.11	0.08
23	42.40548	-70.65672	1/29/2014	0.26	0.04
24	42.40050	-70.64640	1/30/2014	0.49	0.03
25	42.40043	-70.64607	1/30/2014	0.45	0.01
26	42.40361	-70.64634	1/30/2014	0.49	0.02
27	42.40307	-70.64635	1/30/2014	0.51	0.03
29	42.40748	-70.64637	1/30/2014	0.51	0.01
30	42.40127	-70.63678	1/30/2014	0.51	
31	42.40617	-70.64321	1/30/2014	0.55	0.01
32	42.40066	-70.63613	1/30/2014	0.54	0.01
33	42.41456	-70.64361	1/30/2014	0.62	0.00
34	42.40740	-70.65410	1/30/2014	0.36	0.01
35	42.40514	-70.65406	1/30/2014	0.34	0.01
36	42.40042	-70.65480	1/30/2014	0.16	0.02
37	42.41317	-70.65803	1/30/2014	0.30	0.01
38	42.41641	-70.65806	1/30/2014	0.18	0.01
39	42.41673	-70.65430	1/30/2014	0.47	0.02
140	42.40907	-70.65793	12/4/2013	0.29	0.01
143	42.41484	-70.64640	12/4/2013	0.52	

¹ STDEV values are omitted in cases of insufficient data (too few drops per station)

Station number	Lat, deg	Lon, deg	Date, EST	Average penetration depth, m	STDEV penetration depth, m
144	42.41205	-70.65227	12/5/2013	0.42	0.02
145	42.41209	-70.65211	12/5/2013	0.46	0.01
146	42.41198	-70.65230	12/5/2013	0.35	0.09
151	42.41340	-70.65362	12/5/2013	0.39	0.02
152	42.41338	-70.65393	12/5/2013	0.30	0.04
153	42.41334	-70.65411	12/5/2013	0.20	0.04
157	42.40991	-70.64893	12/5/2013	0.54	0.01
158	42.40995	-70.64910	12/5/2013	0.52	0.02
159	42.40848	-70.64752	12/5/2013	0.54	0.03
160	42.40843	-70.64730	12/5/2013	0.55	0.05
161	42.40805	-70.65048	12/5/2013	0.33	0.06
162	42.40796	-70.65031	12/5/2013	0.39	0.02
163	42.41071	-70.64648	12/5/2013	0.55	0.03
164	42.41060	-70.64683	12/5/2013	0.55	0.03
165	42.41486	-70.65087	12/5/2013	0.47	0.01
166	42.41469	-70.65094	12/5/2013	0.25	0.08
167	42.41154	-70.65525	12/5/2013	0.24	0.05
168	42.41168	-70.65537	12/5/2013	0.25	0.08

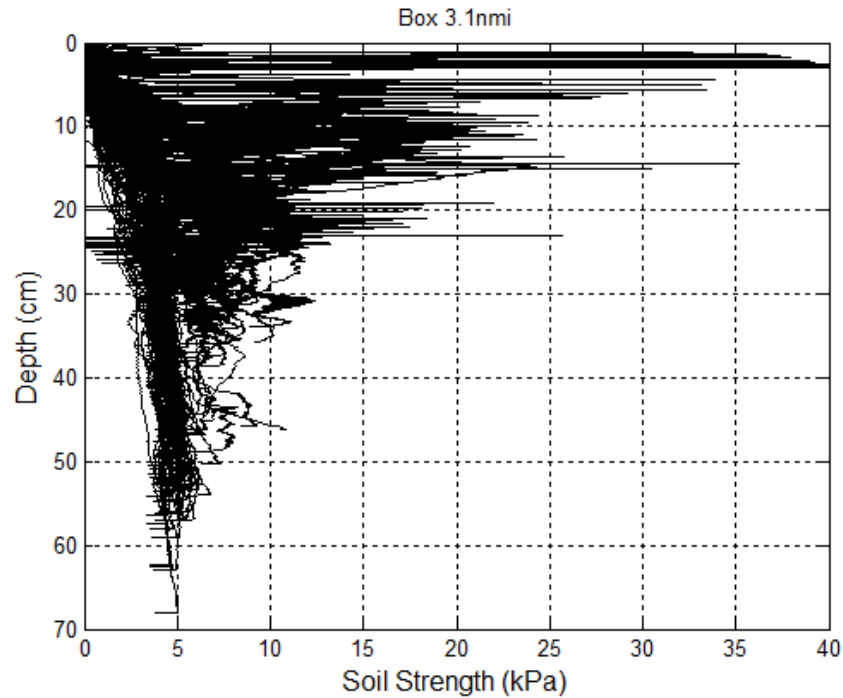


Fig. 4 STING-derived Shear Strength values (70mm foot) vs. sediment depth. Each curve represents an individual STING drop.

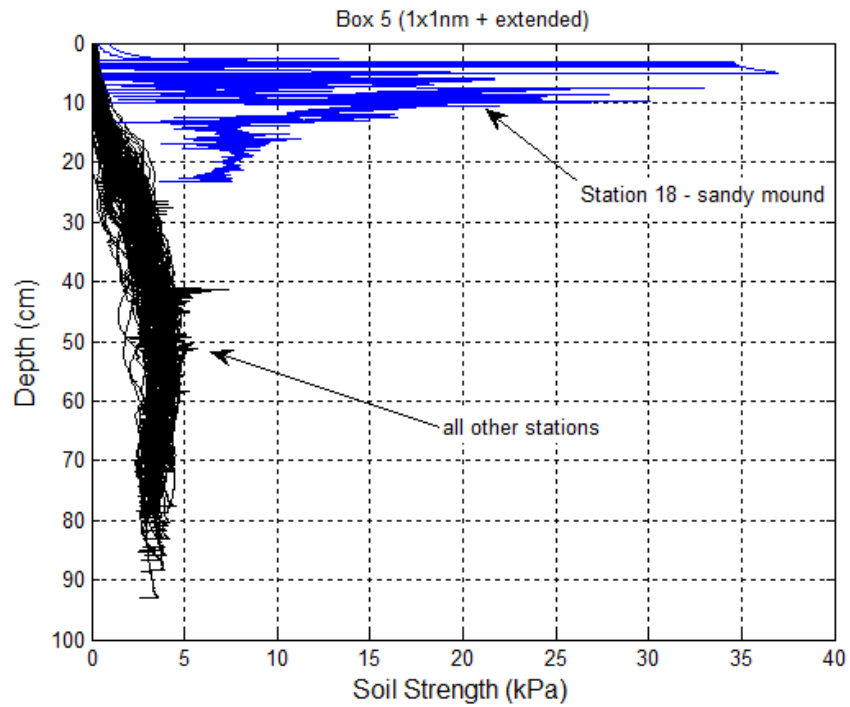


Fig. 5 STING-derived Shear Strength values (70mm foot) vs. sediment depth. Each curve is an individual STING drop. Three drops at station 18 (blue) are shown as being distinctly different from the rest of the ensemble (black). Overall uniformity over the entire are is high, describing a soft clayey sediment type

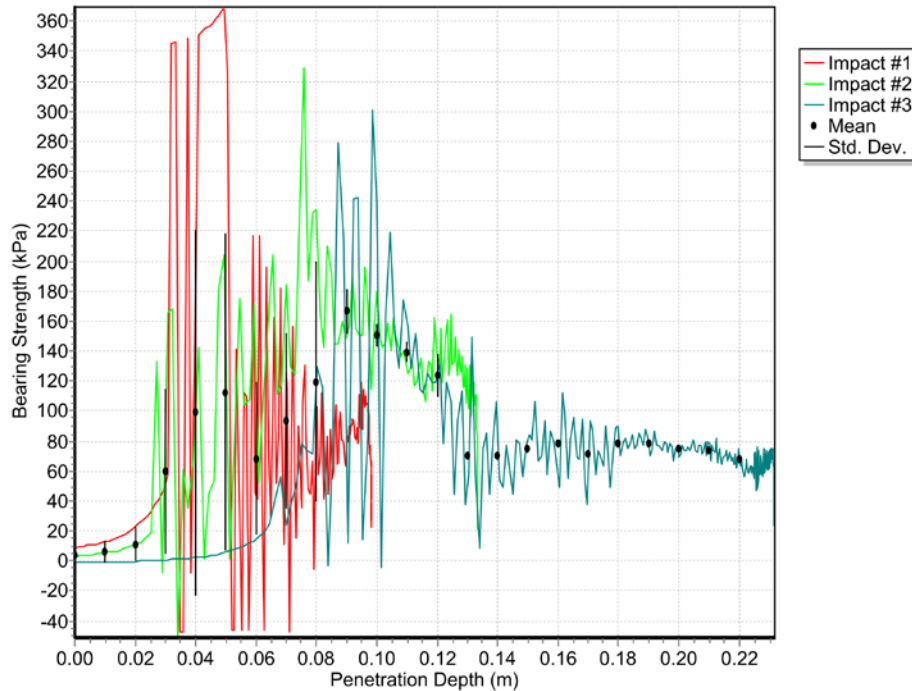


Fig. 6 Bearing strength profile at Station #18, Box 5 (STING: 2m rod, 70mm foot, water depth: 81m)

The exact extend of this mound, based on the STING results alone, is less than the spacing between the stations (or less than 500m), since all of the adjacent test sites demonstrate normal response, characteristic of the soft clayey material of the area in Box 5, with no discernable presence of sandy layers at the surface or in depth. If overlaying the STING deployment stations with data available from Google EarthTM, the mound is apparent (Fig. 7), confirming the deposition of a foreign (to this area) likely dredged material that appears to be mostly sand. Presence of sand at about 3cm in depth with some soft material over the top, as well as a developed seafloor settlement on the perimeter of the mound, also visible in the figure, indicates that this is not a recent deposition. Considering 0.3cm/yr approximate soft sediment deposition rates in this area (*Alperin et al.*, 2002; *Crusius et al.*, 2004), one may estimate that the dump occurred approximately 10 years ago.

Examination of all the penetration histories (see Appendix A) indicates that no sandy layers of any significant extent were detected at the other stations in Box 5, except for station 18. Some such spikes and oscillations in the acceleration (and therefore bearing strength) record are only occasionally present at several stations in Box 5, other than Station 18, with perhaps, only one drop out of typical three per station, exhibiting this response. These are best attributed to a sudden deceleration of the probe when hitting a single shell or a similarly-sized marine organism or other obstruction in the sediment. If not repeated in all drops on that station or in the same area, such a single event is an unlikely indicator of sandy layer (or lens) of any significant extent.

Fig. 8 shows the values of maximum penetration burial of the 70mm STINGs in Box 5 as well as the surrounding area explored. Most of the box shows relatively even distribution of burial values, indicating essentially similar sediment with exception of the northern portion, discussed above.

The results of the STING burial in Box 3.1 are given in Fig. 9, with both nautical chart and sediment class overlays. The sediment appears to be quite variable, with one station yielding a penetration burial of over 60cm whereas another of only 11cm. As is also evident from Fig. 4, most stations contain significant presence of sandy layers, resulting in high dilation values and overall low penetration. The details of all the bearing strength measurements for this location are also given in Appendix B, showing the prevalence of the oscillatory behavior caused by these dilative effects.

While attempting to classify the sediment in Box 3.1 according to the maximum STING burial values, also indicative of burial of much larger bodies, as discussed above, a contour map was computed from the point data. While sparse, resulting in some contour irregularities, it is nonetheless notable in identifying a portion of Box 3.1 with softest material. Similar contour plotting for Box 5 was found to be not informative due to the overall similarity of the material, with the exception of the bottom mound feature.



Fig. 7 STING positions with an overlaid bathymetric image (Google DigitalGlobe™, 2004), showing the abnormality near the NW corner of Box 5 – a mound that may have resulted from dredged material dumping

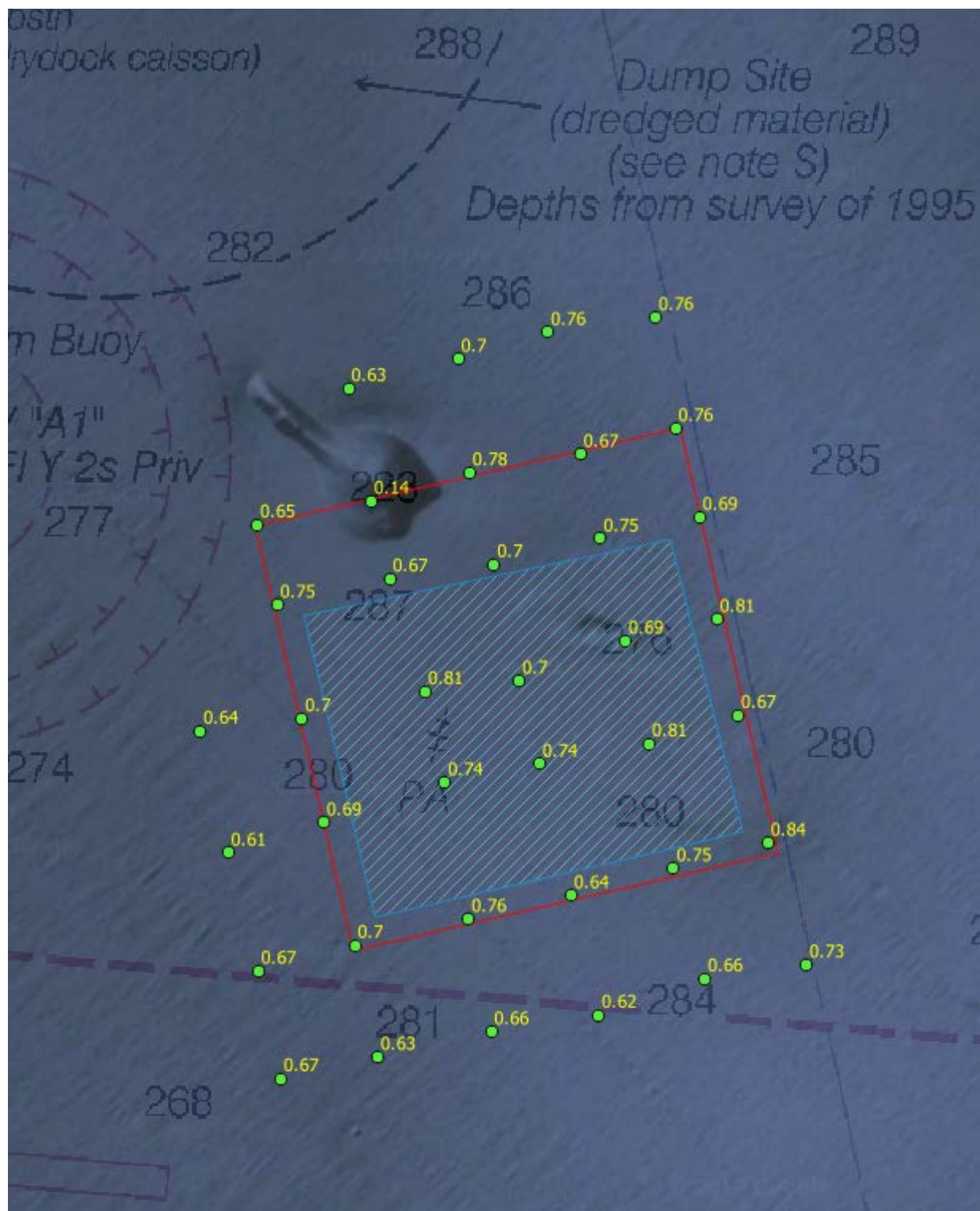


Fig. 8 Maximum burial depths (STINGs 70mm, each value – an average of three drops), with bathymetry (Google DigitalGlobe™) and Nautical Chart overlays, and a selected area of potential impact burial of at least 70cm

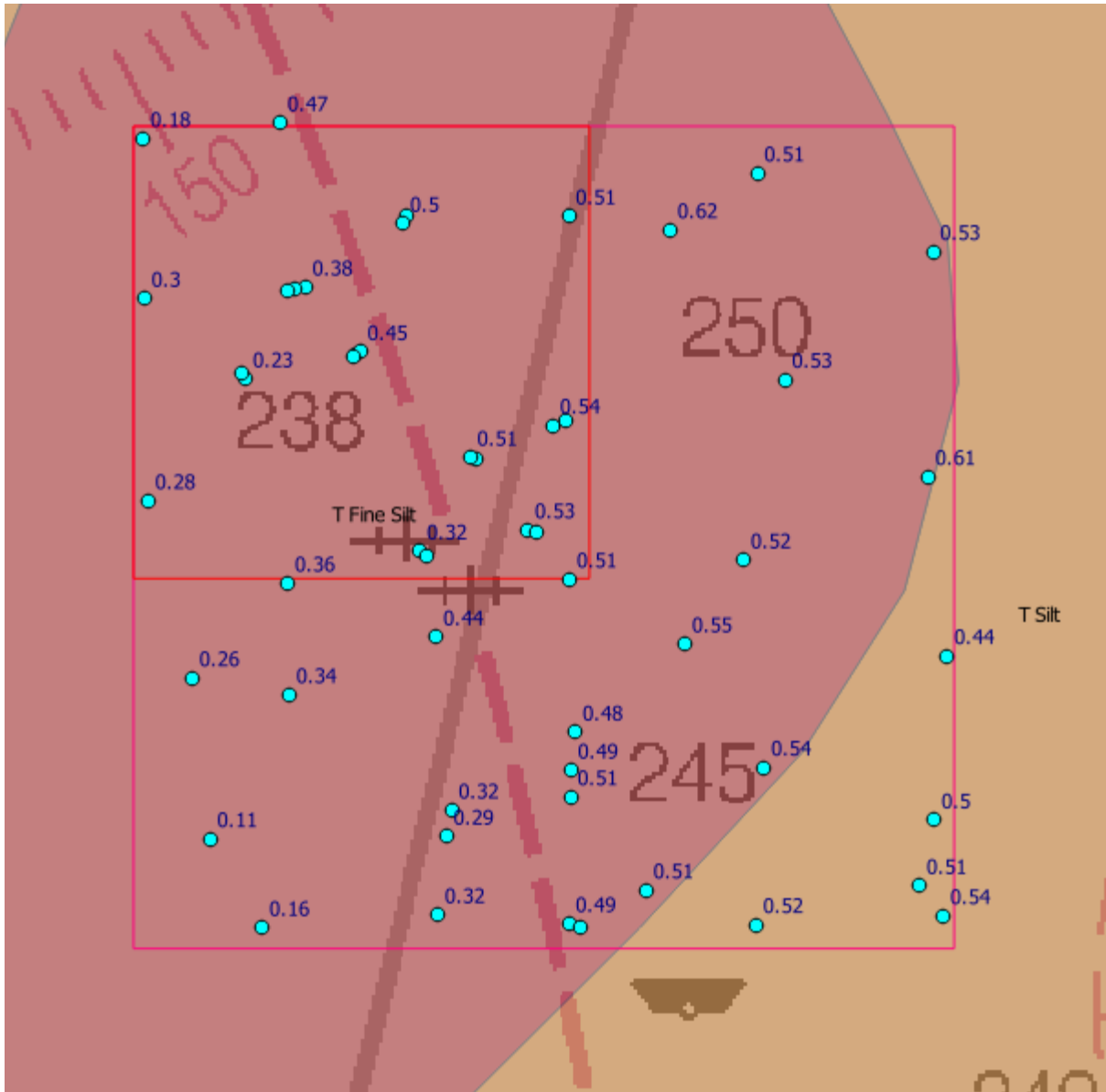


Fig. 9 Maximum burial depths (STINGs 70mm, averages of several drops, in meters), with the Nautical Chart overlay. Larger area is Box 3.1nmi, small area inside it (NW part) is Box 3

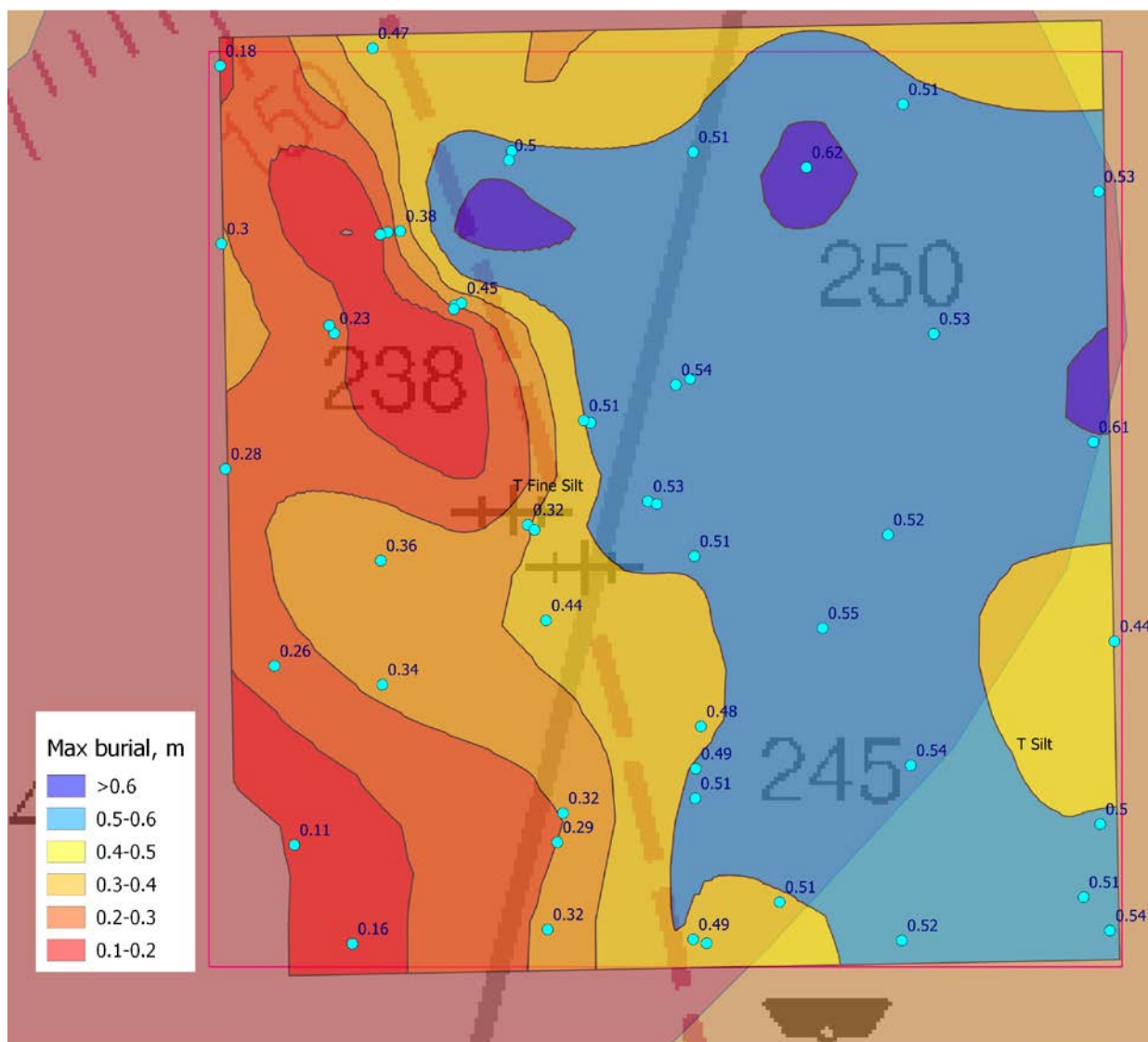


Fig. 10 Contours of maximum burial depth (STING 70mm), Box 3.1nm. Individual STING maximum burial values are shown for each station. Shading is assigned by using an average value between two adjacent contour lines. NAVOCEANO sediment data chart is included as an overlay, with majority of Box 3.1nm defined as Terrigenous Fine Silt. All burial depths are in meters.

Summary

In summary, the overall shear strength of the sediment encountered in Box 5 is significantly lower than that in Box 3.1, with no observable presence of sandy layers in much of the box. This results in higher impact burial values and a larger area where these high values may be found. Box 3.1, on the other hand, contains not only sediment that appears coarser (mostly silt, vs. mostly clay), but also includes many locations with significant sandy layering, which severely impedes impact penetration burial.

A preferred area of the softest sediment with greatest potential for high impact burial may thus be identified in Box 5, as shown approximately in Fig. 8, occupying the majority of the initial box and somewhat away from the sandy mound, found near the Northern boundary. The coordinates of this preferred box are as follows:

Field	Lat, deg	Lon, deg
NW	42.38782	-70.57281
NE	42.39073	-70.55382
SE	42.37955	-70.55006
SW	42.37628	-70.56912

A slow transition into more silty sediments begins West and South-West of this identified area, where STING-70 penetration burial depths, and therefore expected burials of larger objects, begin to decline gradually.

Acknowledgments

Assistance in STING deployments by the personnel of NRL Code 7130, the crew of r/v Matthew Hughes (Boston Harbor Cruises), and the staff of Bluefin Robotics Co. is acknowledged.

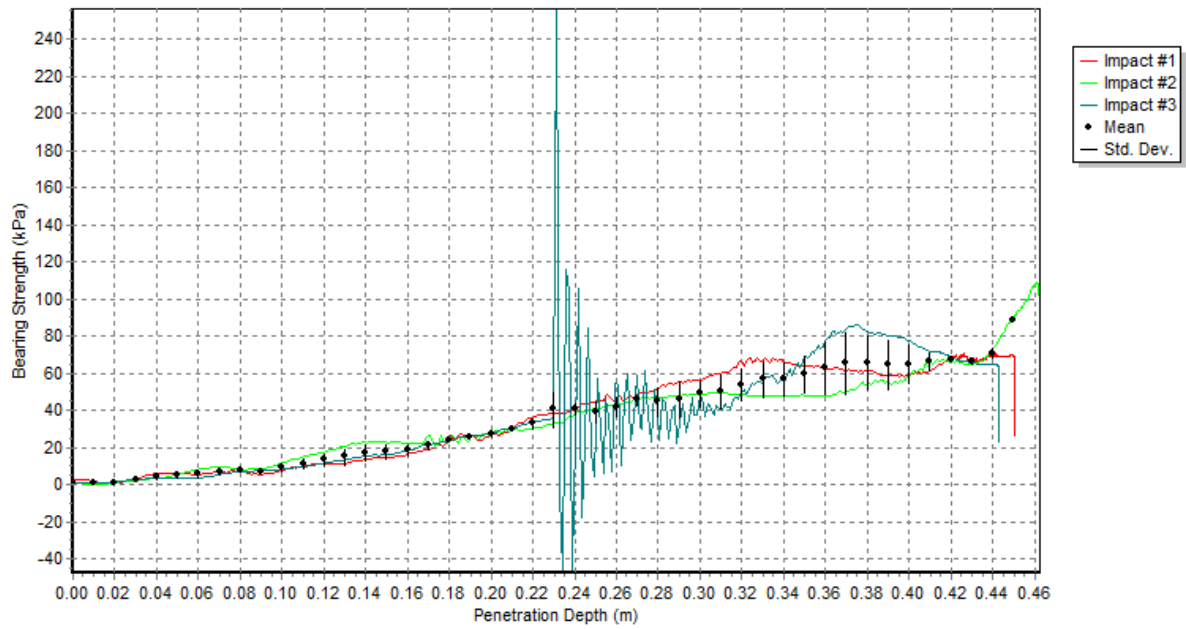
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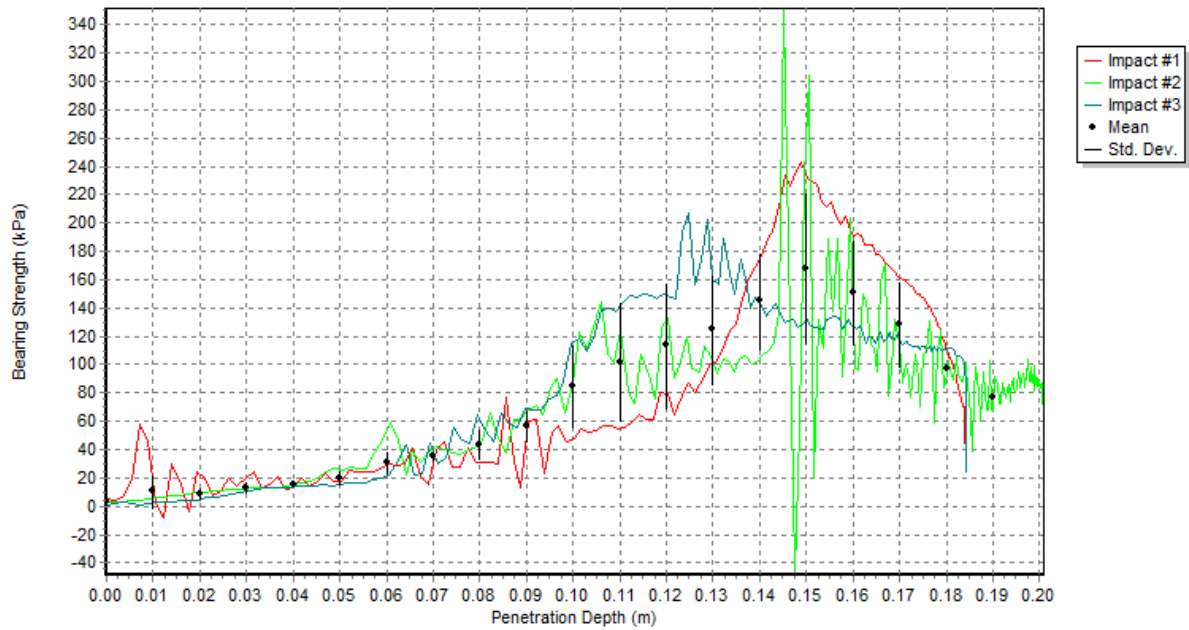
Appendix A STING data – bearing strength profiles with depth. Bo3.1nmi

Note: negative bearing strength values that appear near zero sediment depth in some drops (or averages) are artifacts of STING software processing or minor inconsistencies in sensor calibrations and have no physical meaning. This is possible in cases of very soft surficial material (as it is here), when the water-sediment interface is often not well defined and is difficult to determine from deceleration records (either via native automated STING processing or by manual selection). Practically, these negative values should, of course, be all positive. In all cases, these inconsistencies are minor and are well within the overall accuracy of the instrument in sediments of this type.

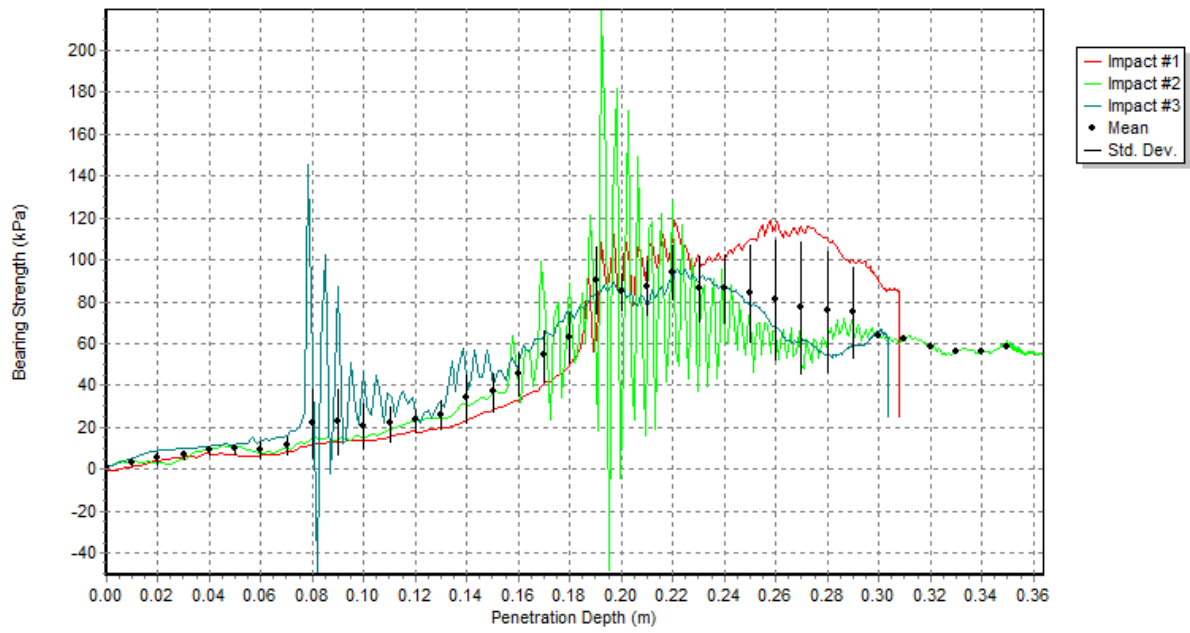
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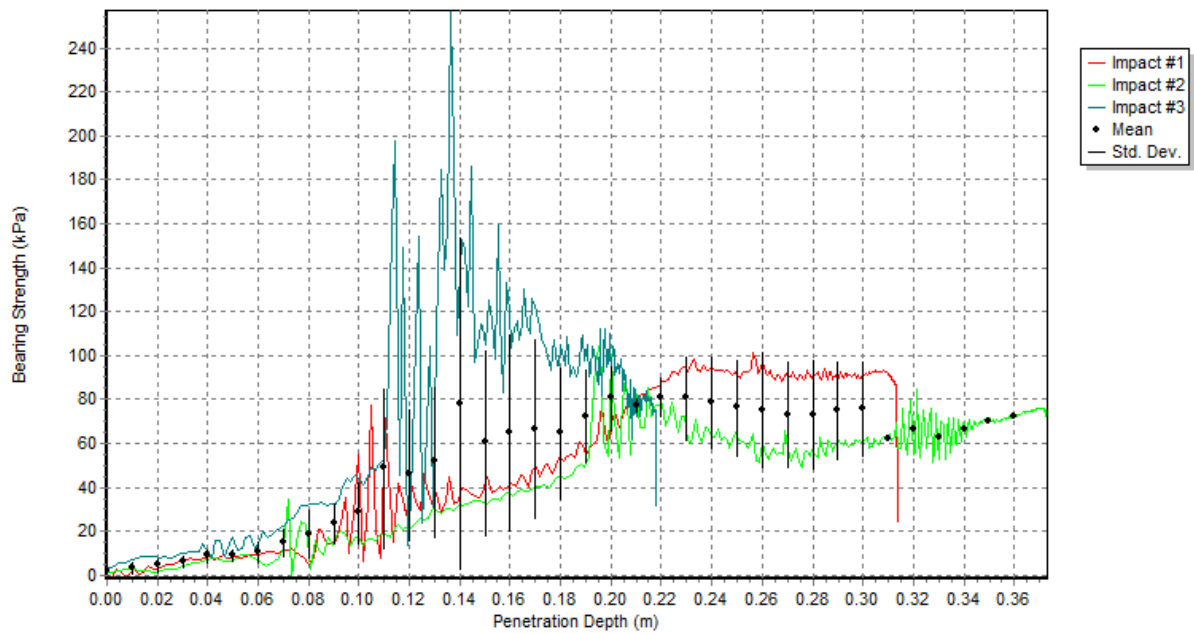
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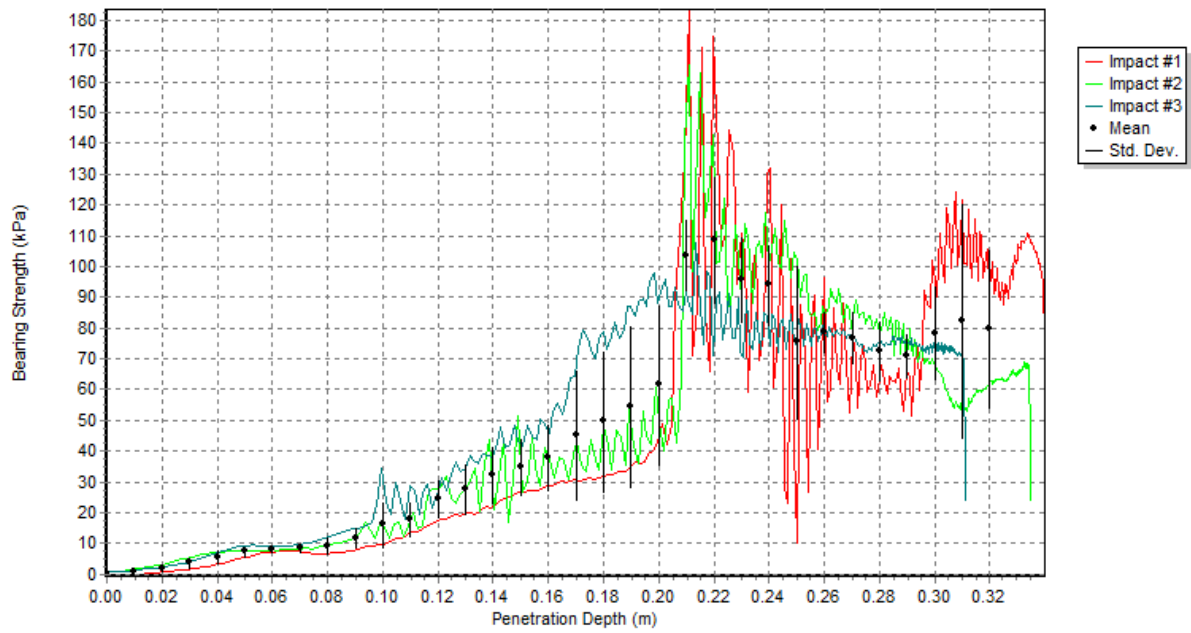
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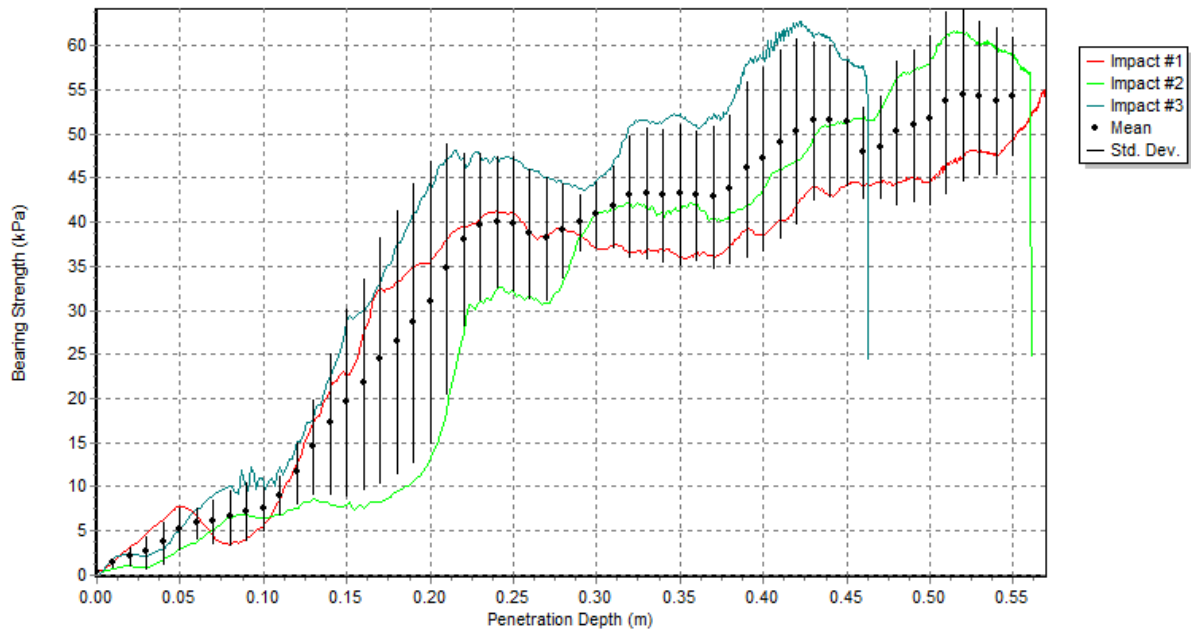
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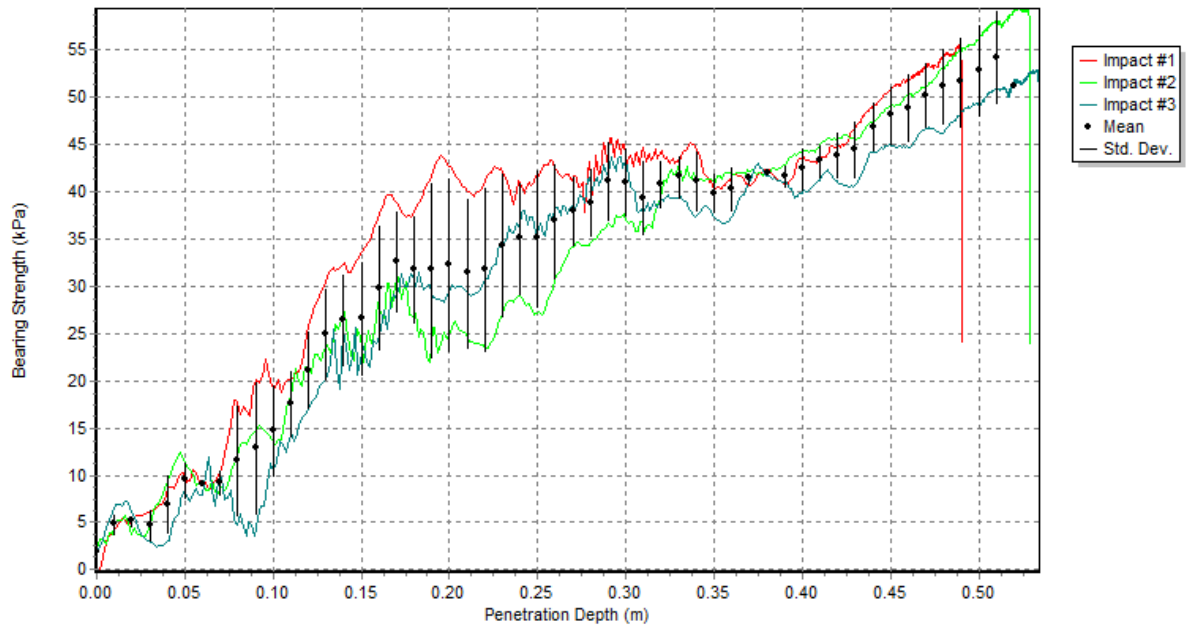
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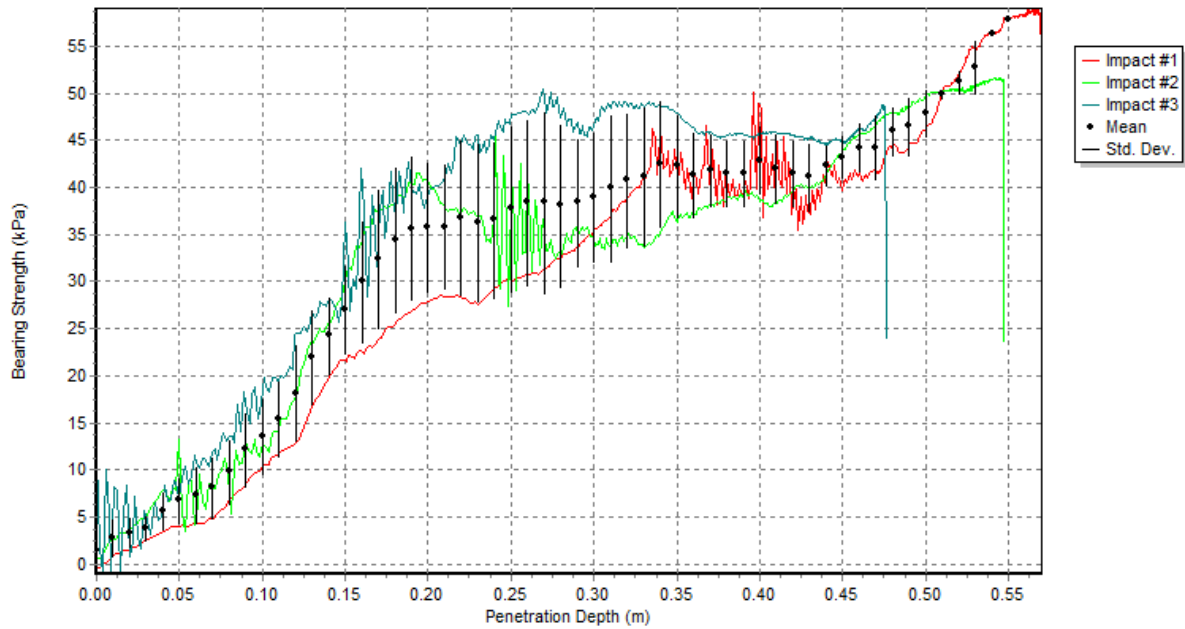
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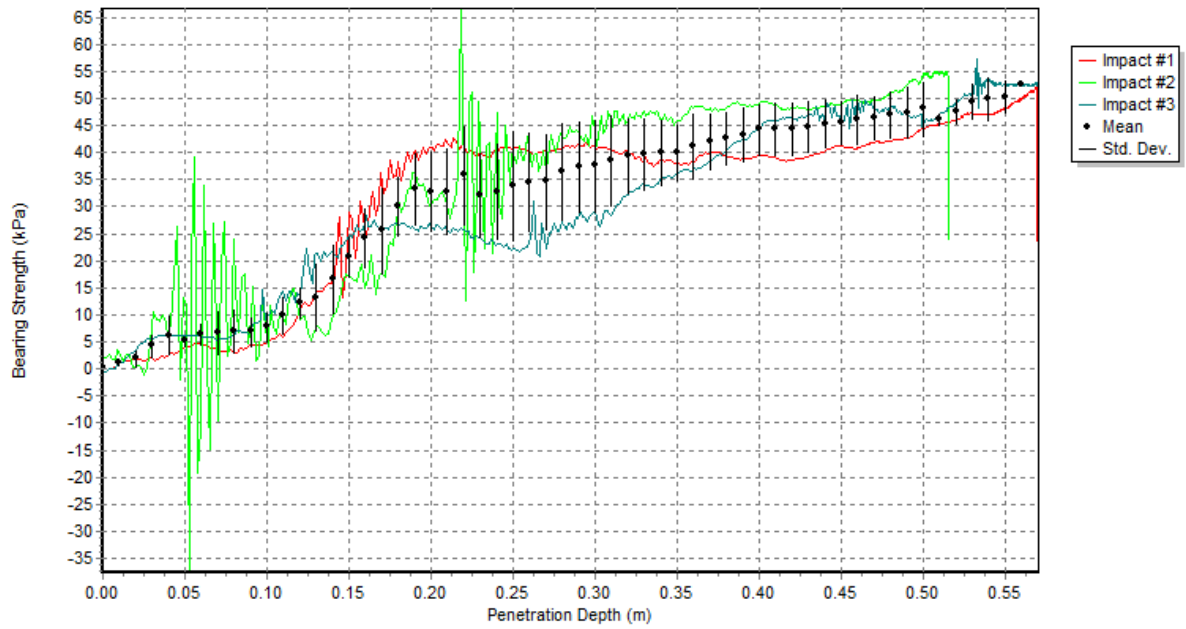
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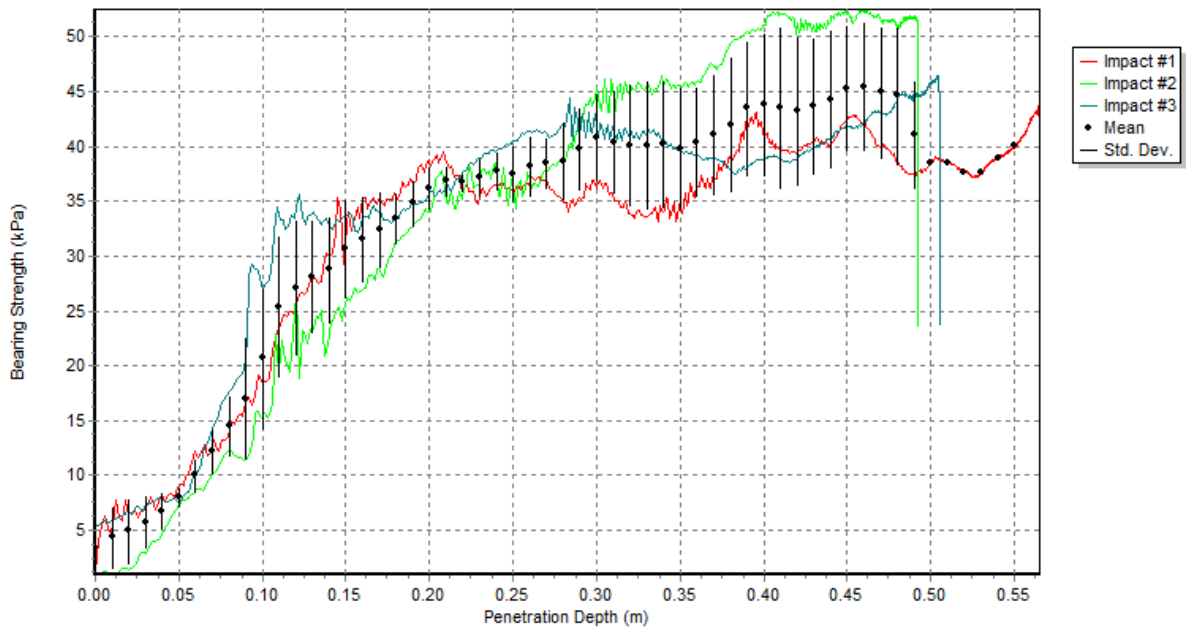
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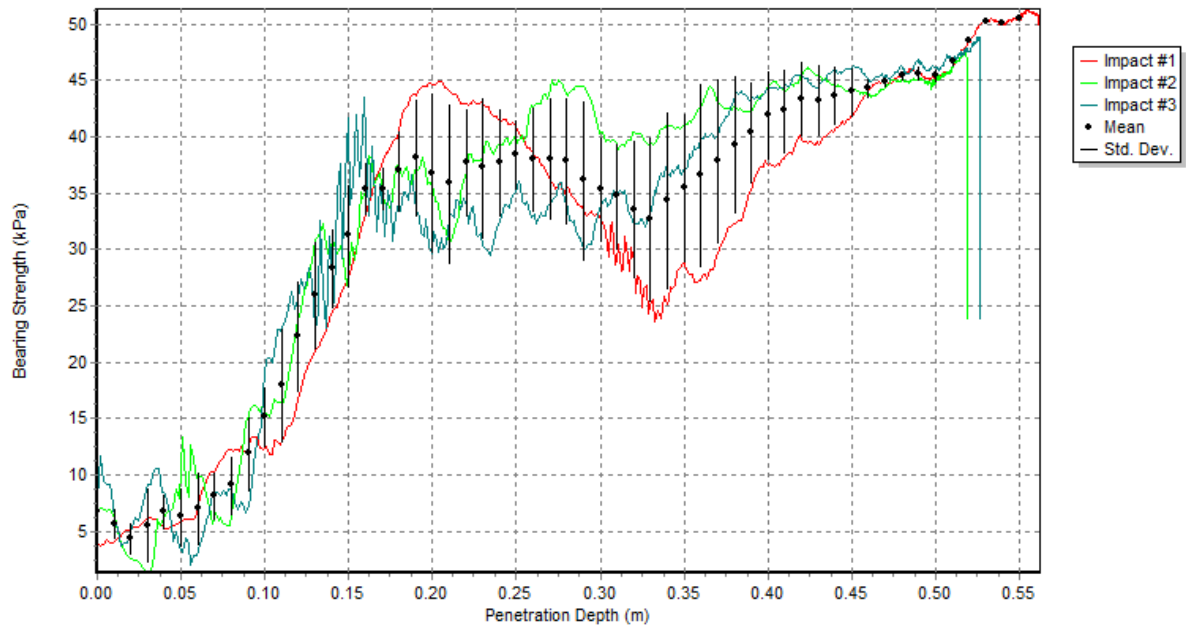
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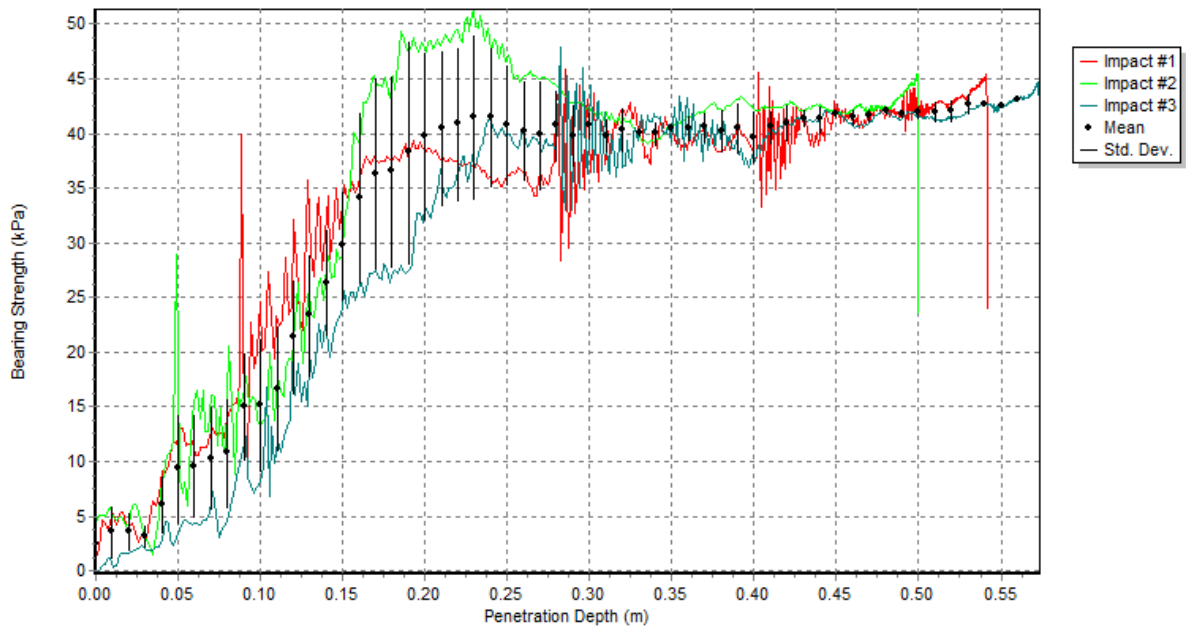
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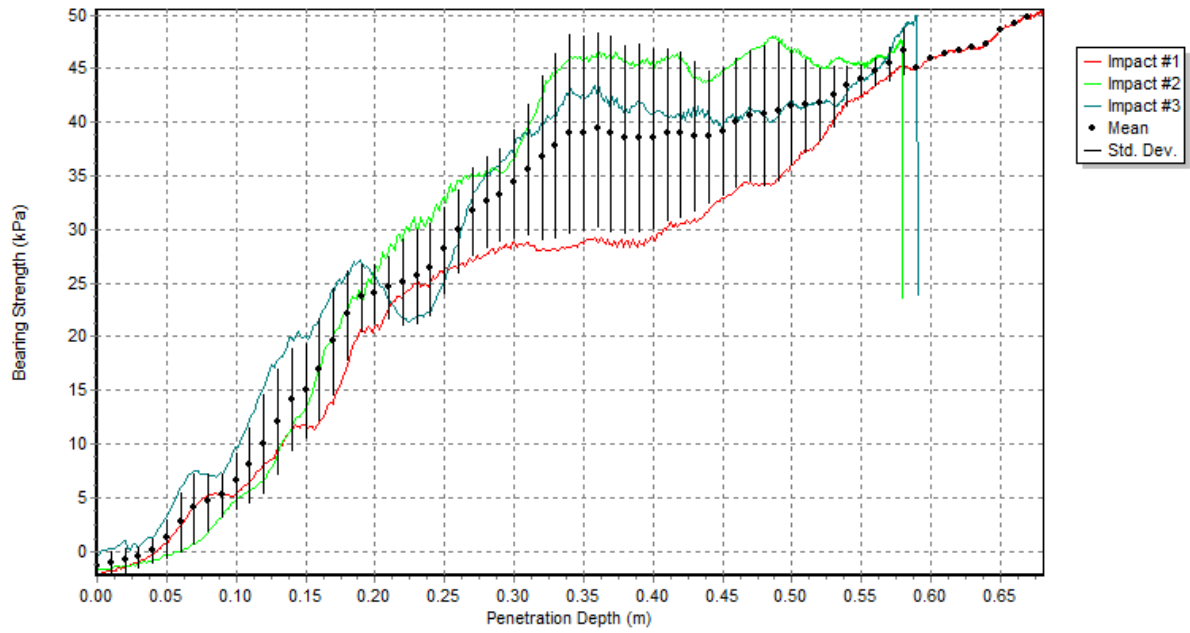
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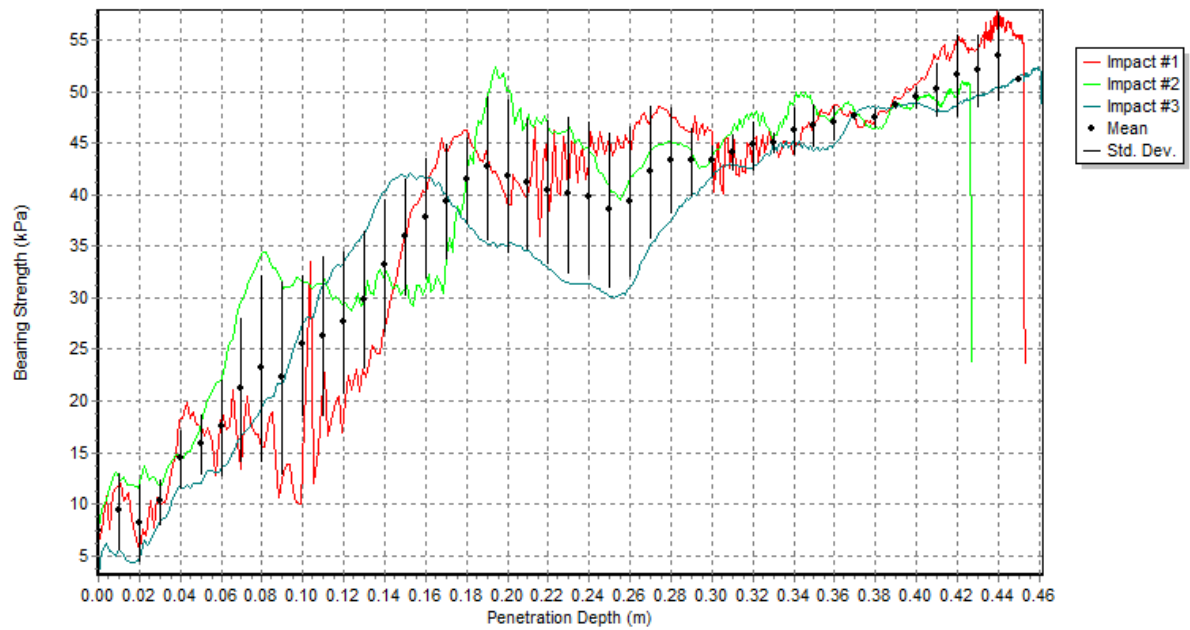
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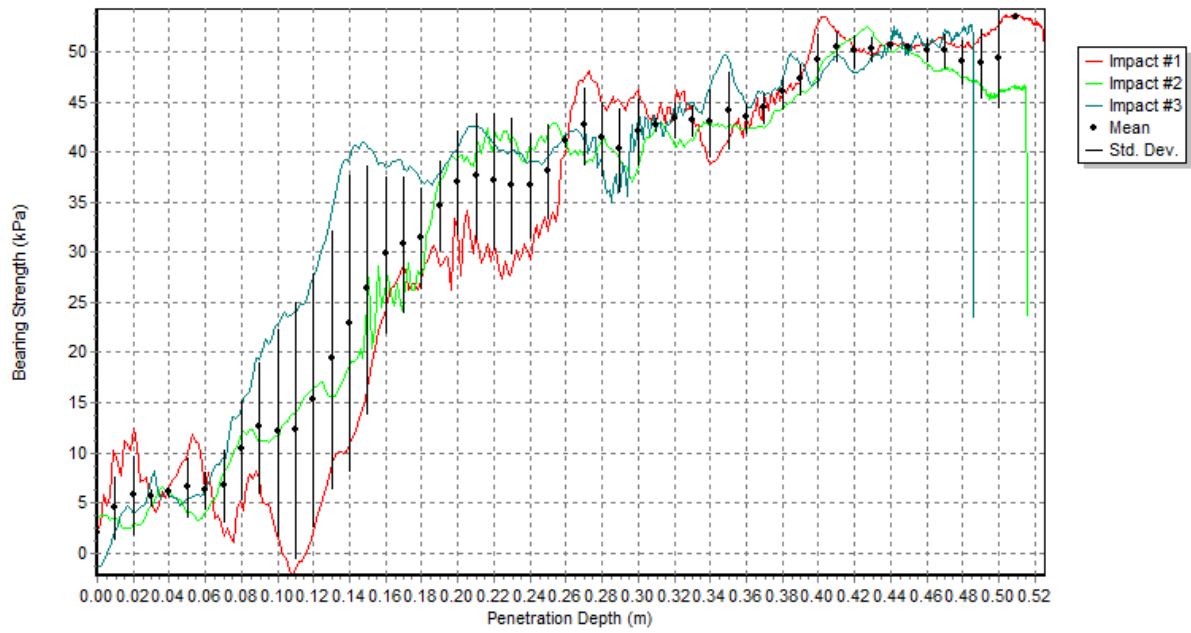
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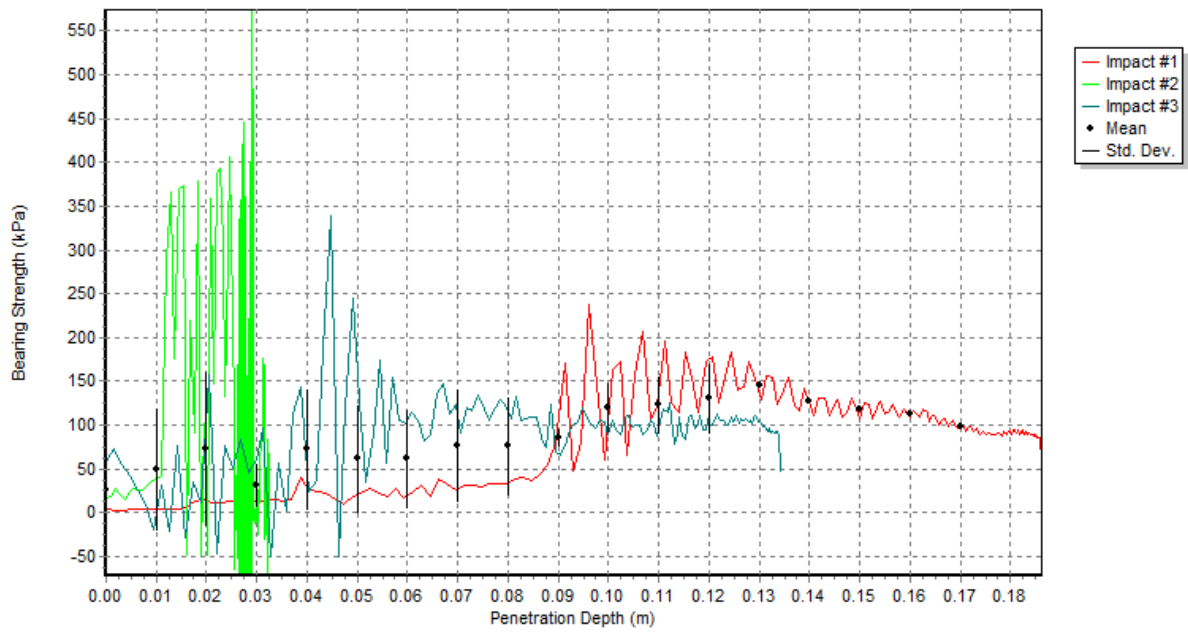
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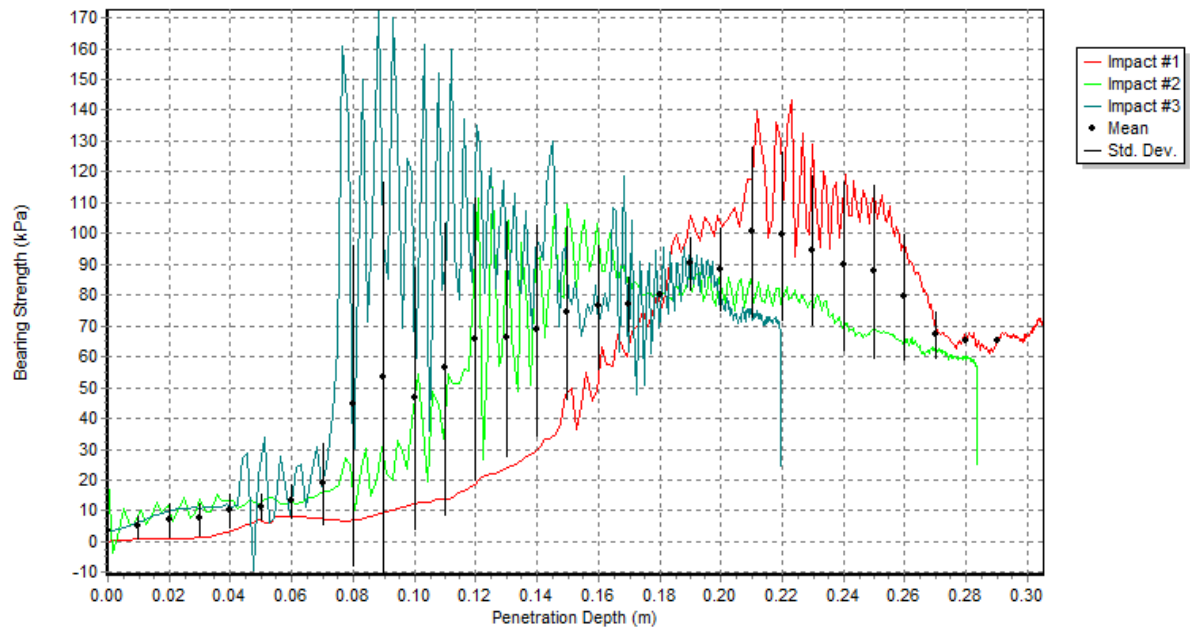
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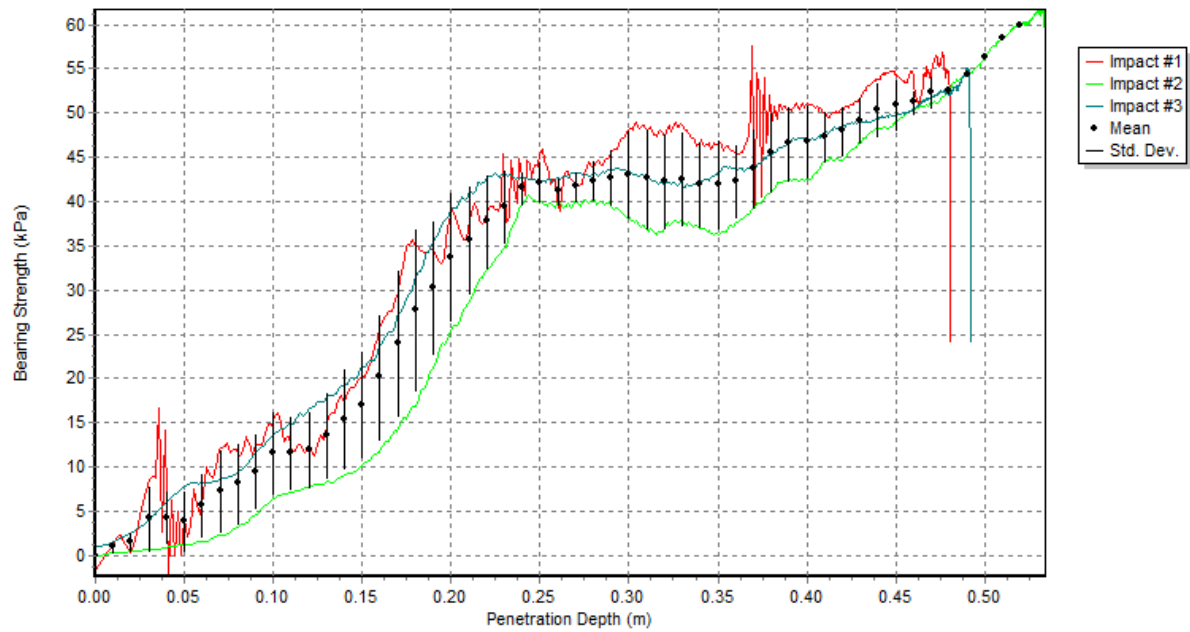
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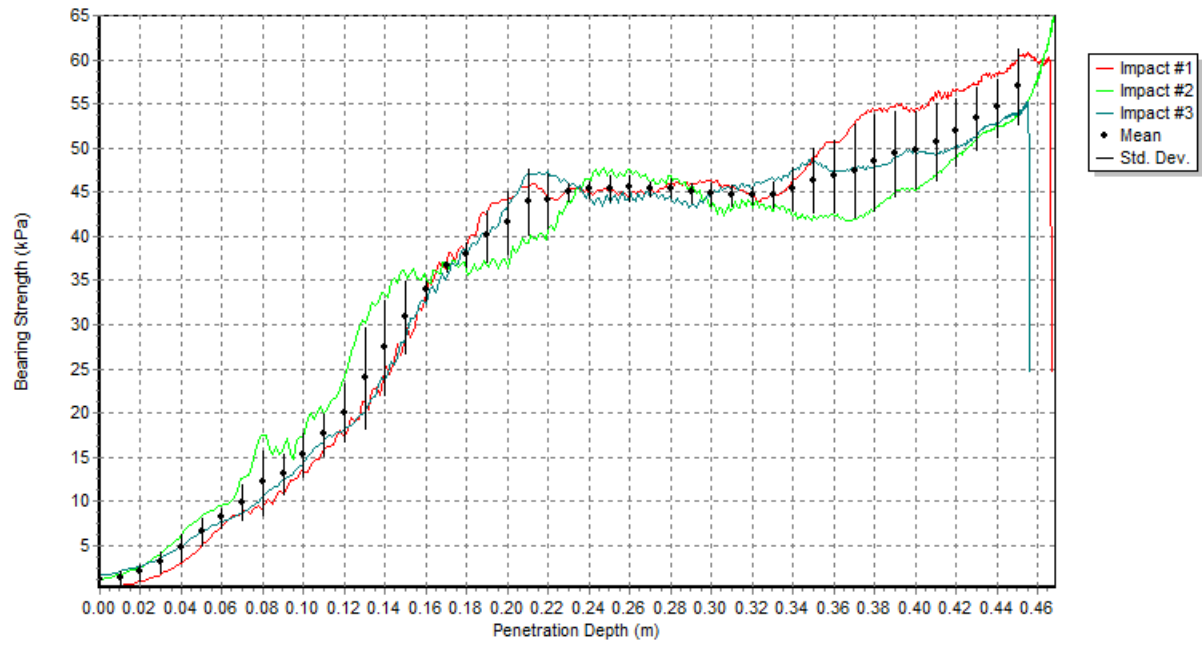
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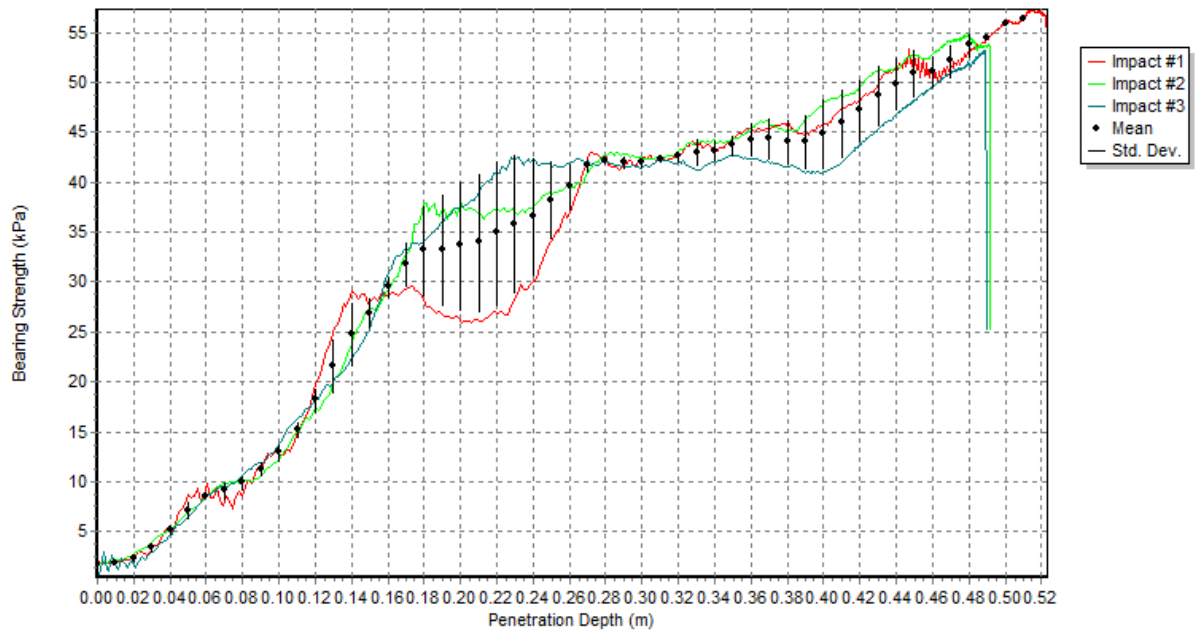
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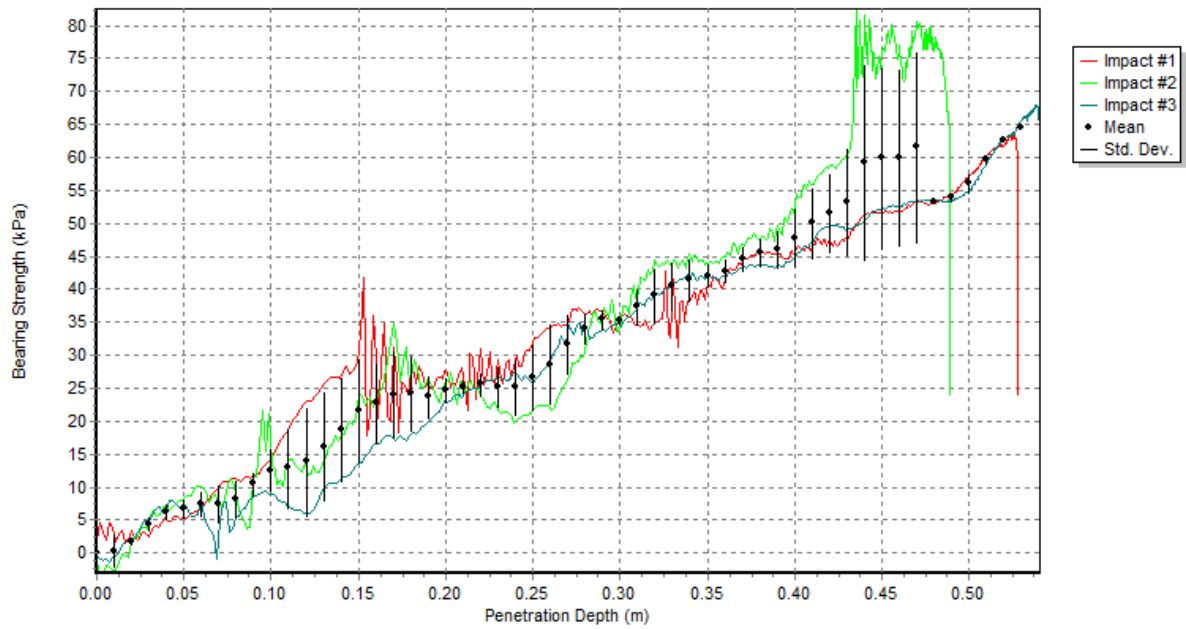
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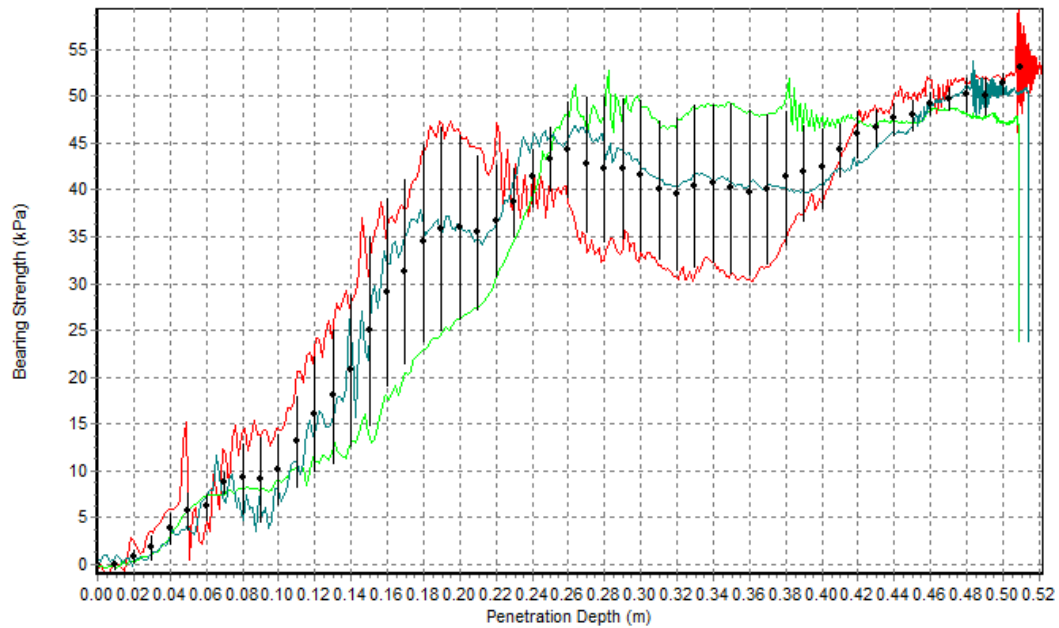
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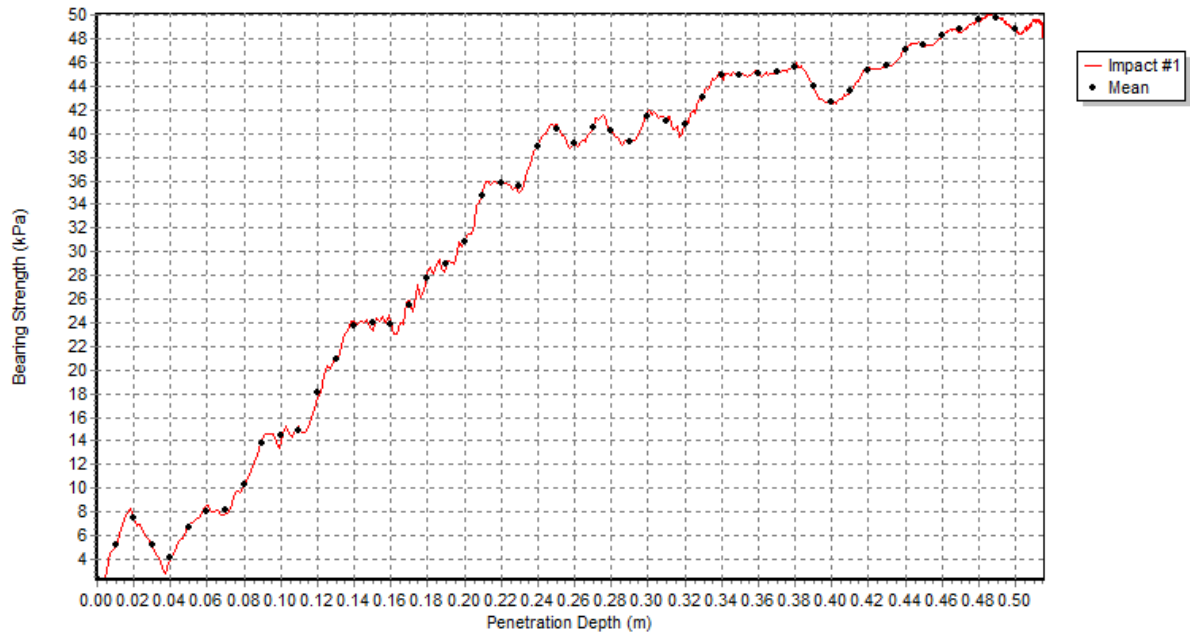
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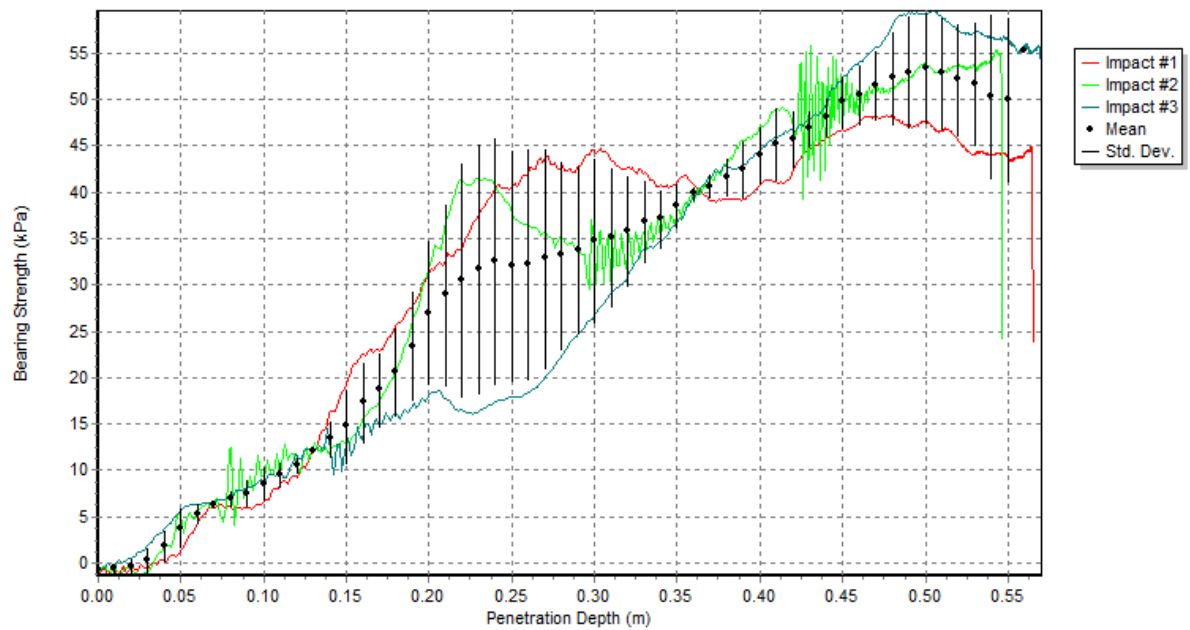
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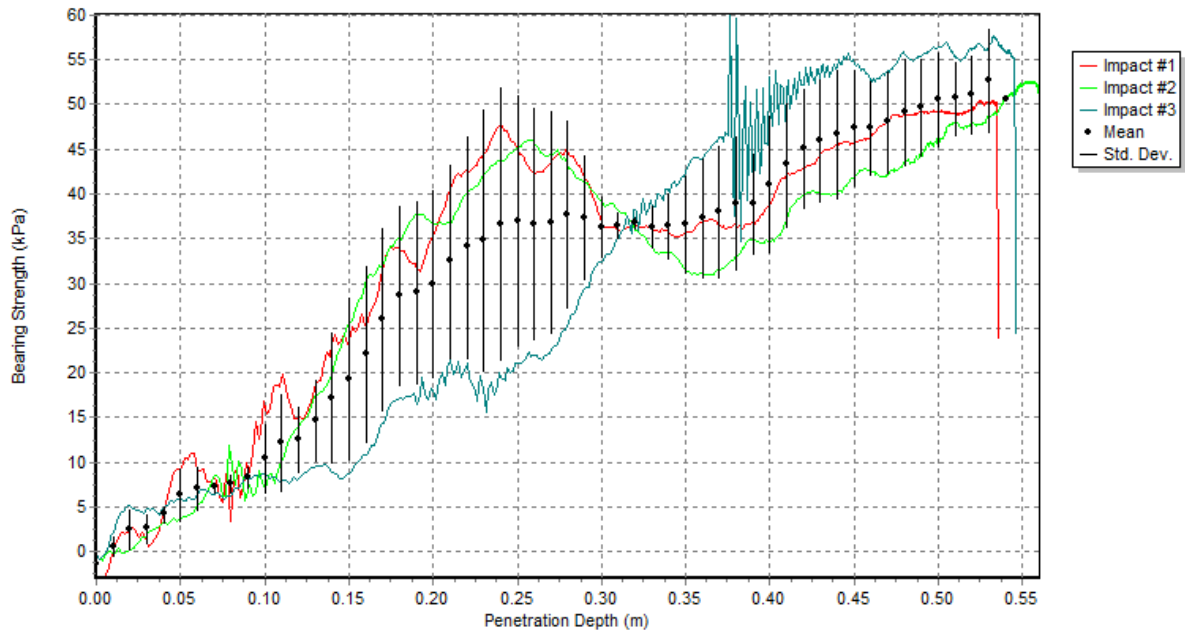
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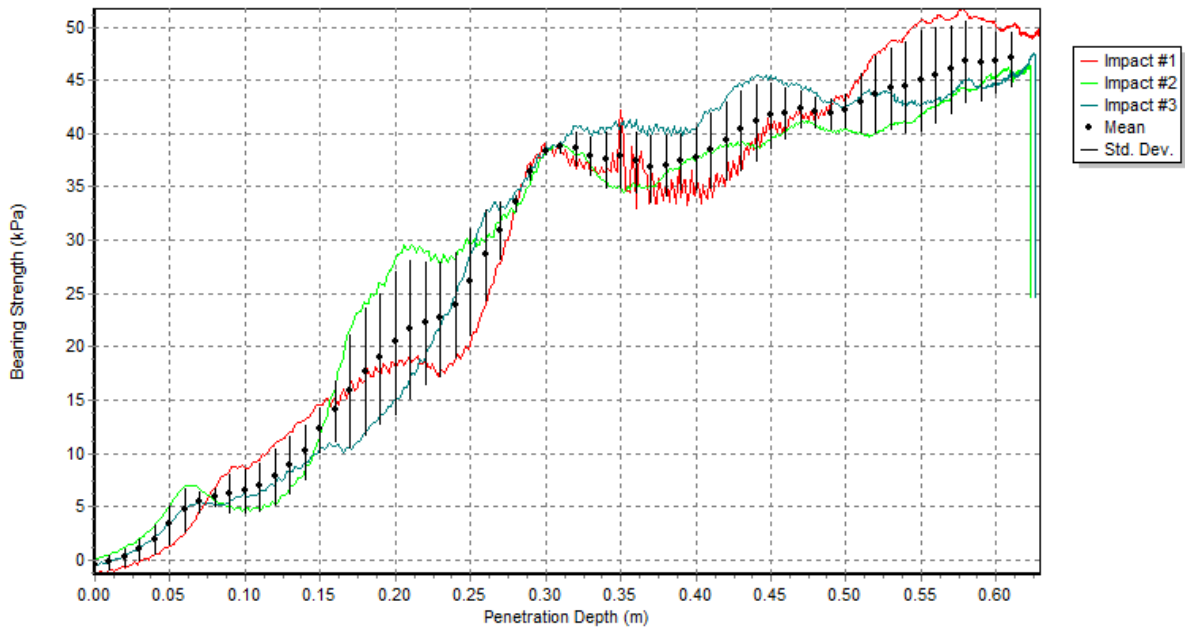
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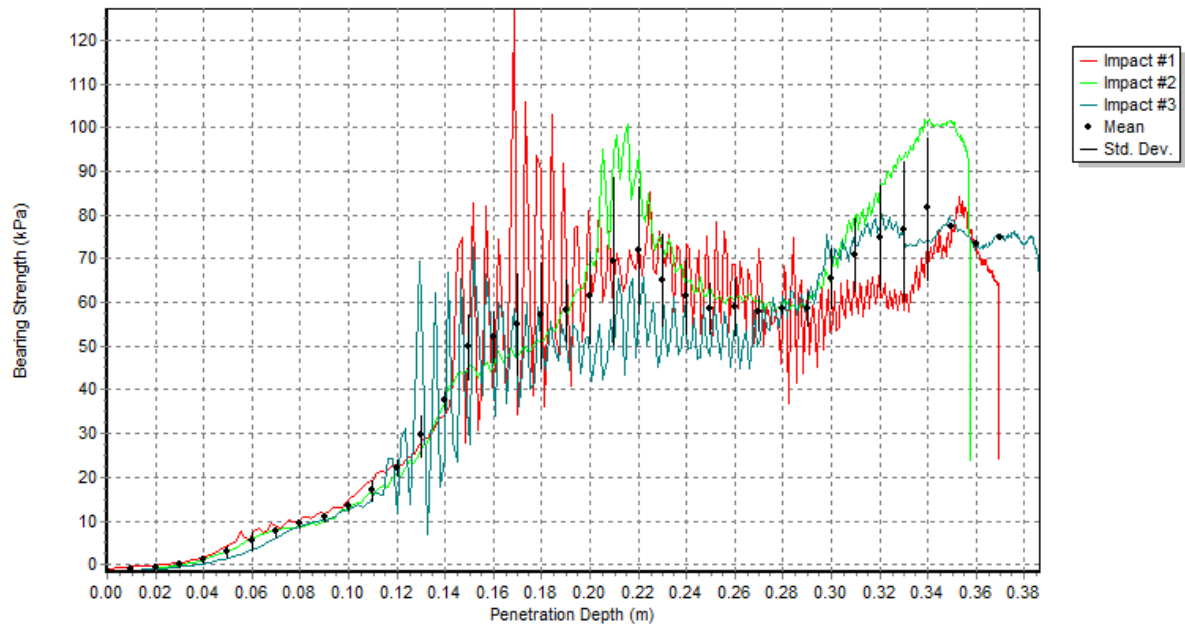
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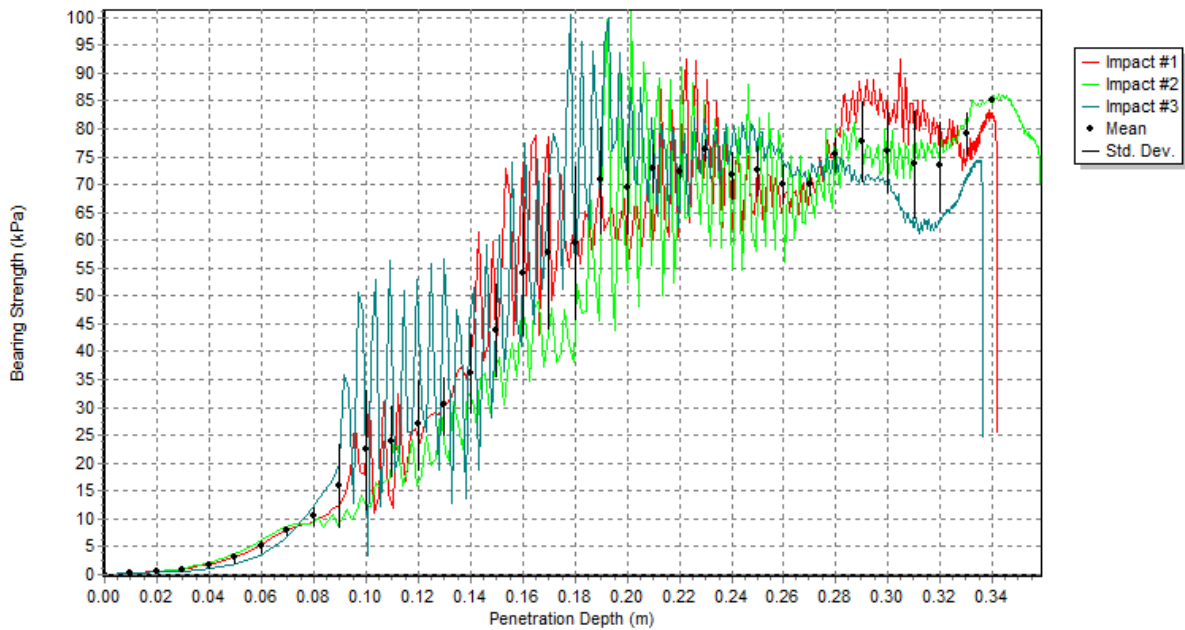
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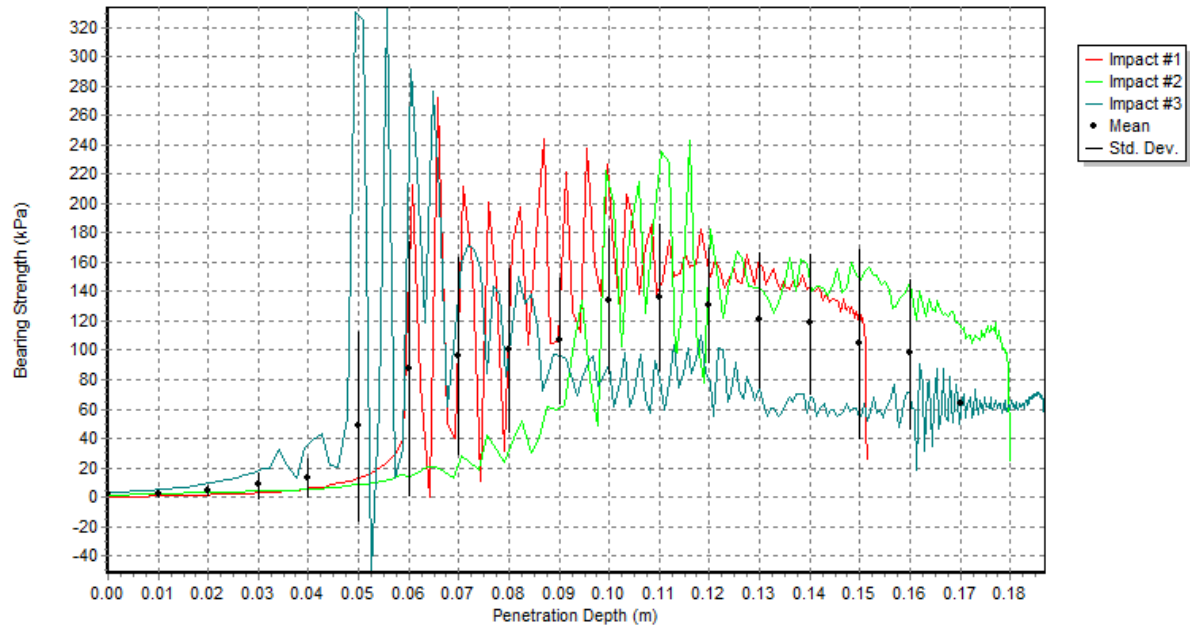
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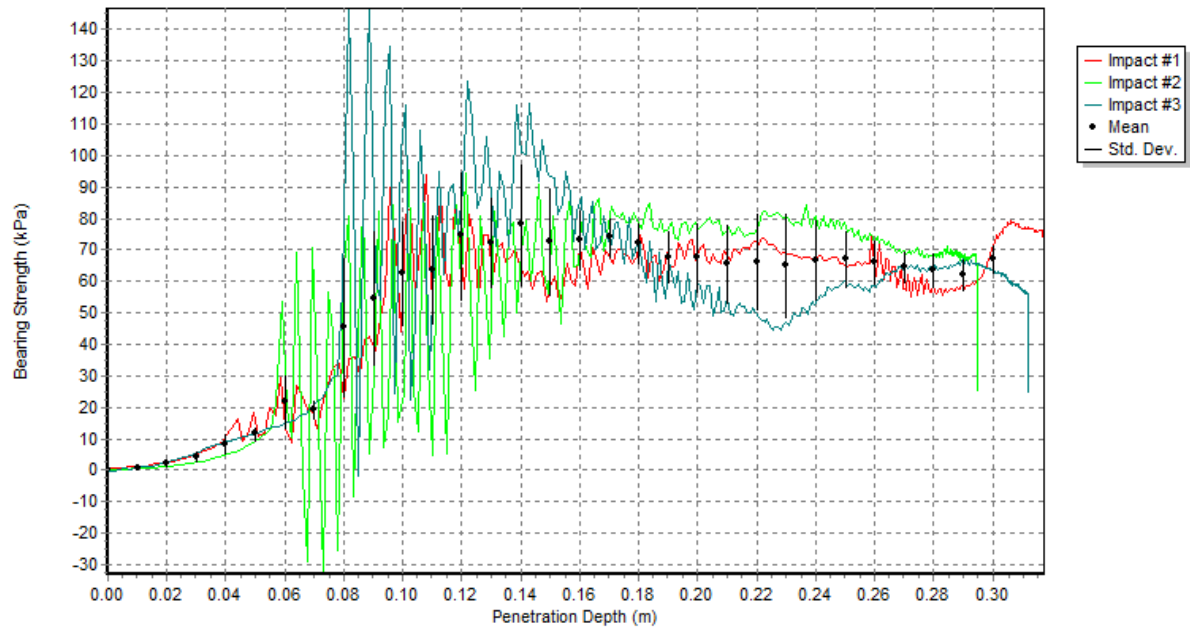
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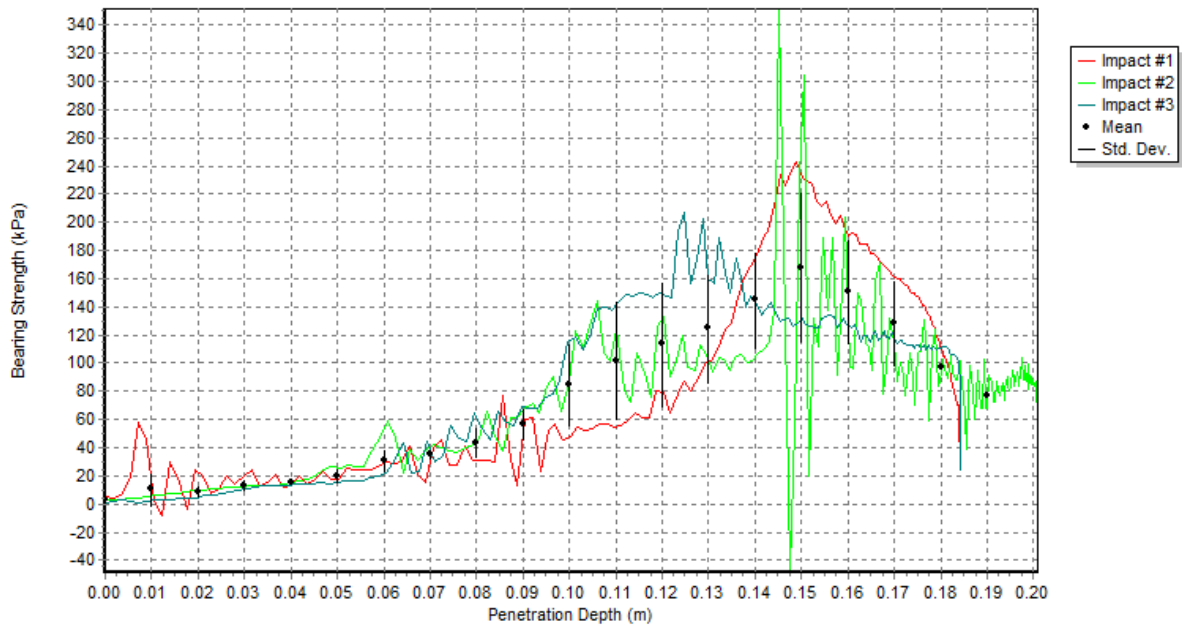
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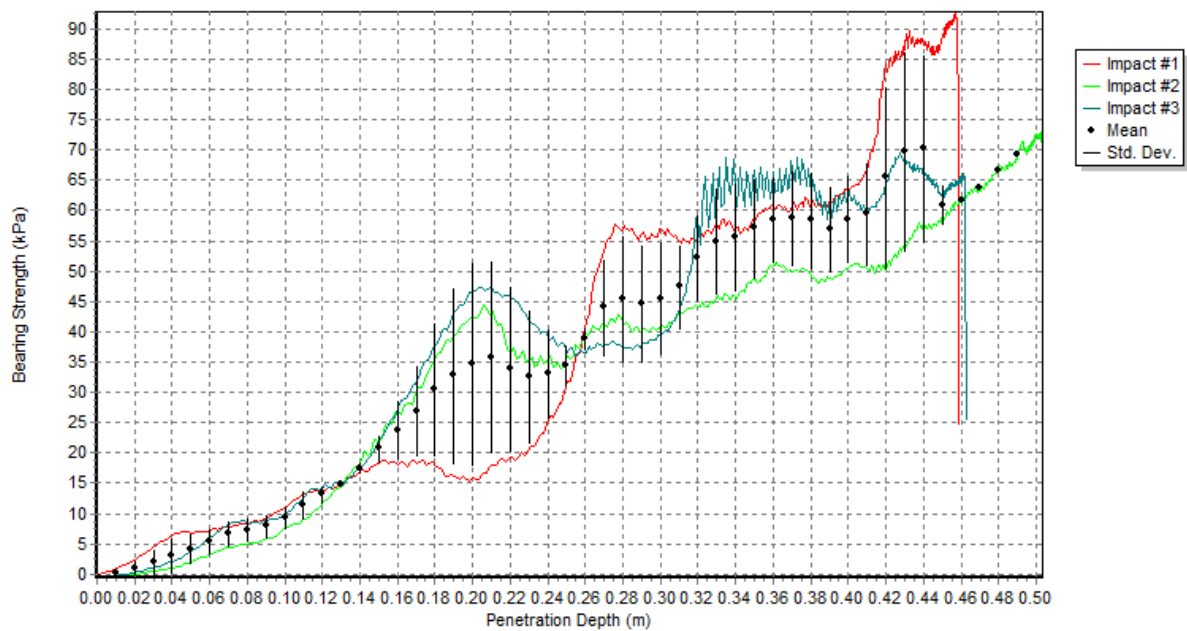
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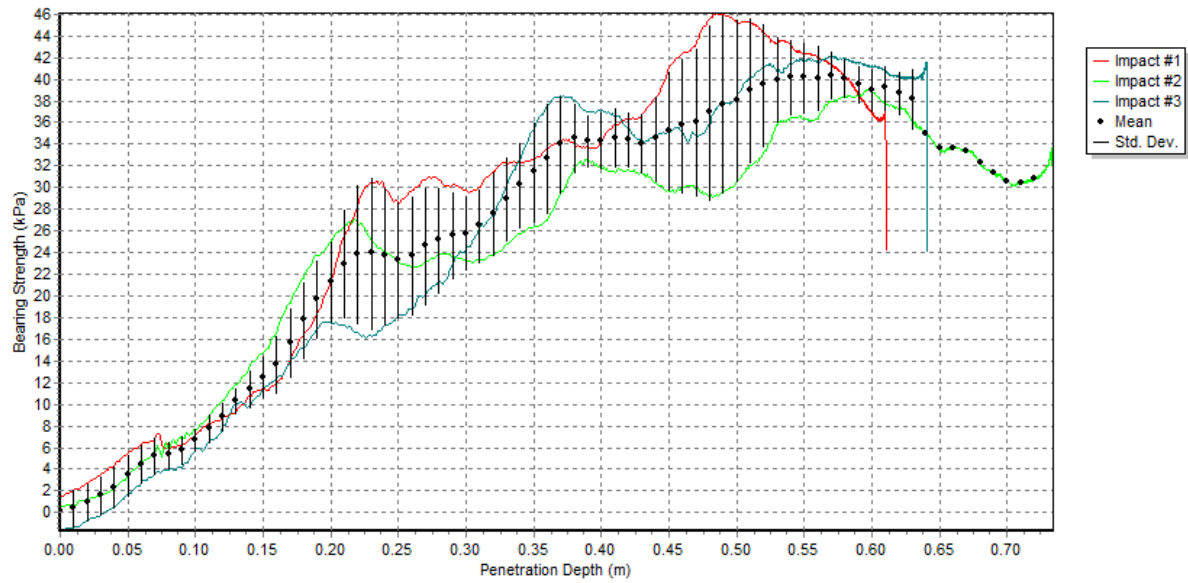
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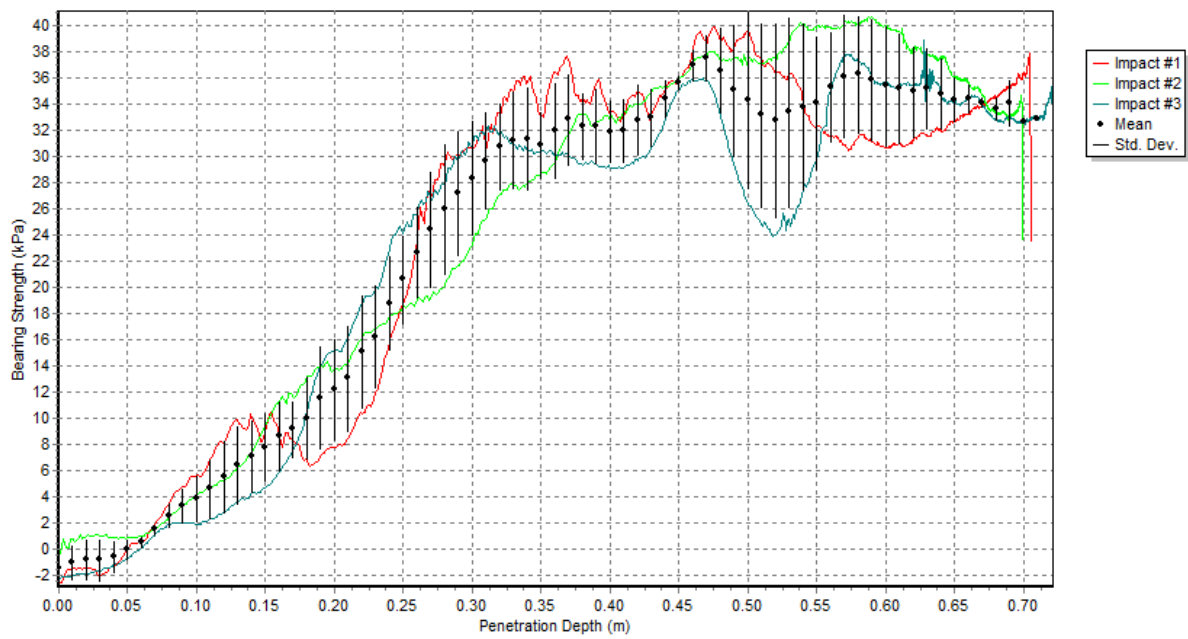
Appendix B STING data – bearing strength profiles with depth. Box 5.

Note: negative bearing strength values that appear near zero sediment depth in some drops (or averages) are artifacts of STING software processing or minor inconsistencies in sensor calibrations and have no physical meaning. This is possible in cases of very soft surficial material (as it is here), when the water-sediment interface is often not well defined and is difficult to determine from deceleration records (either via native automated STING processing or by manual selection). Practically, these negative values should, of course, be all positive. In all cases, these inconsistencies are minor and are well within the overall accuracy of the instrument in sediments of this type.

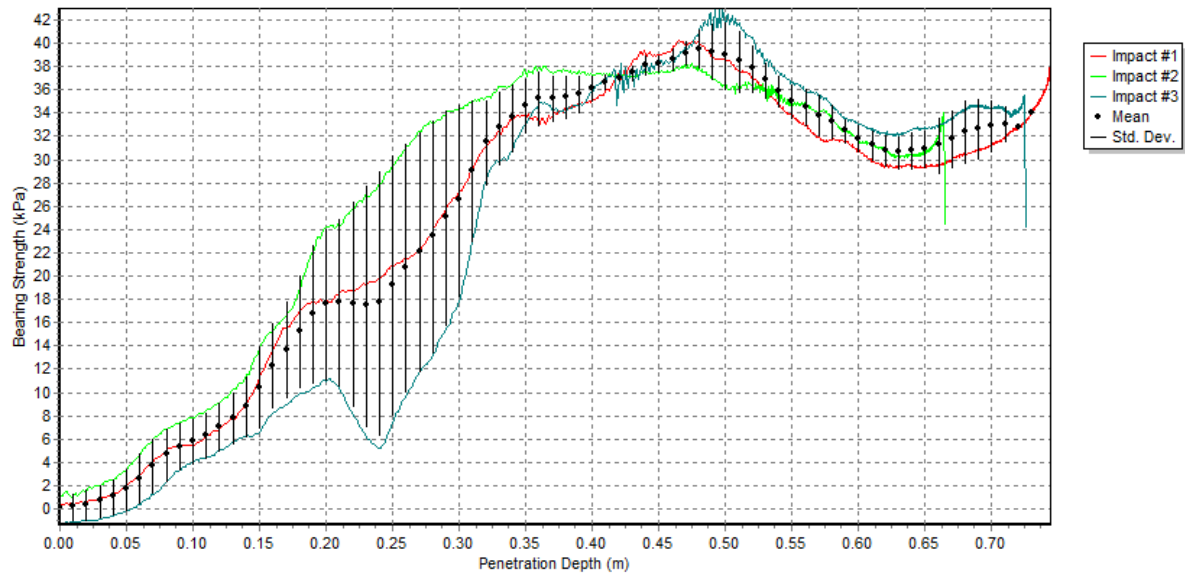
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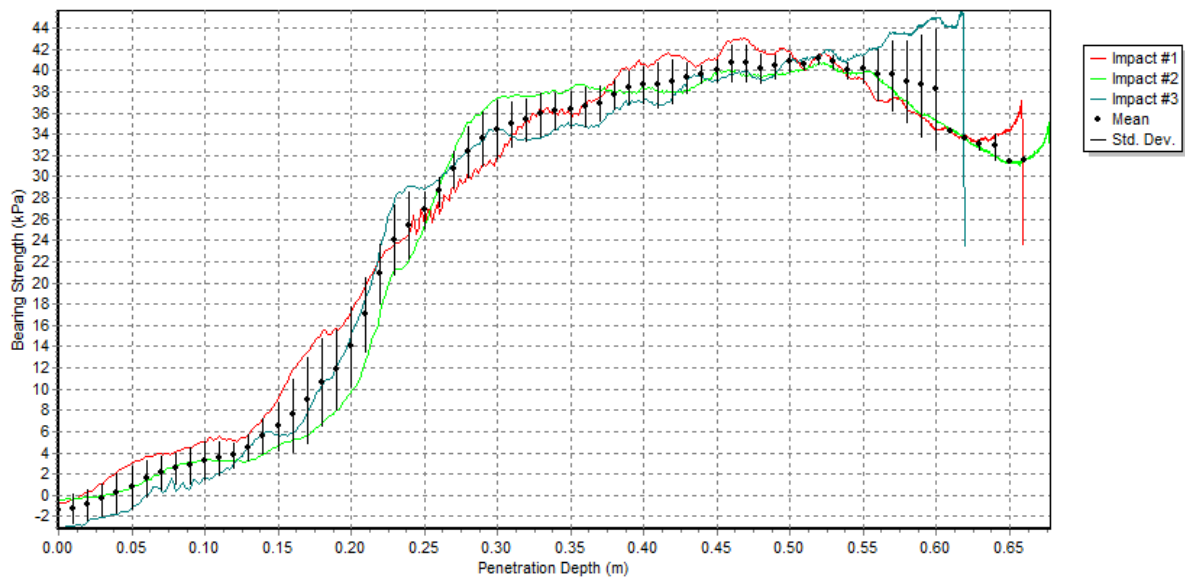
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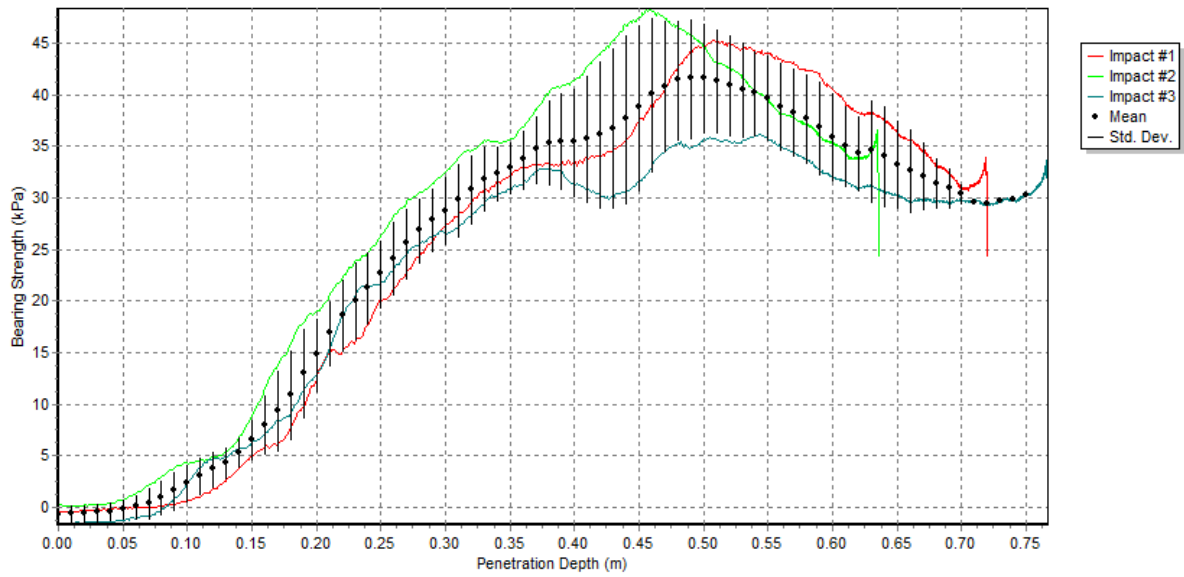
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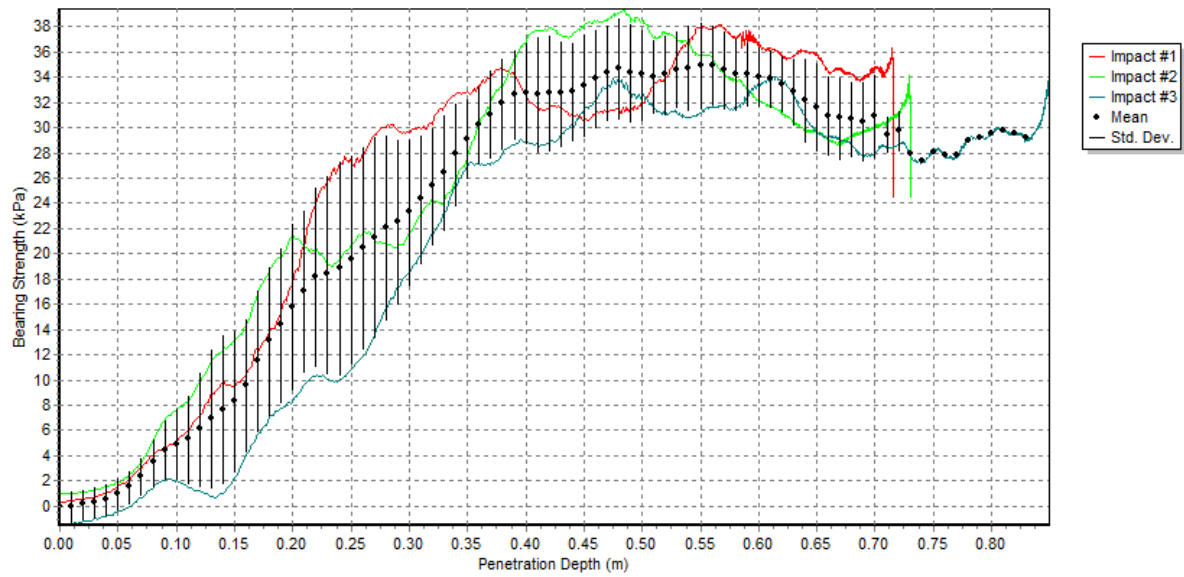
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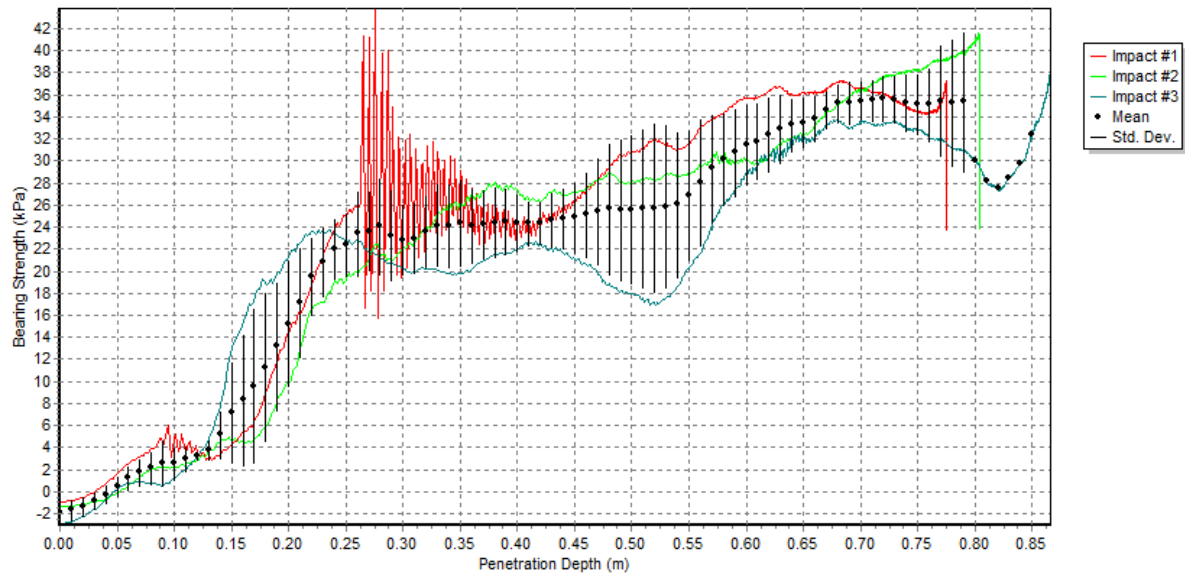
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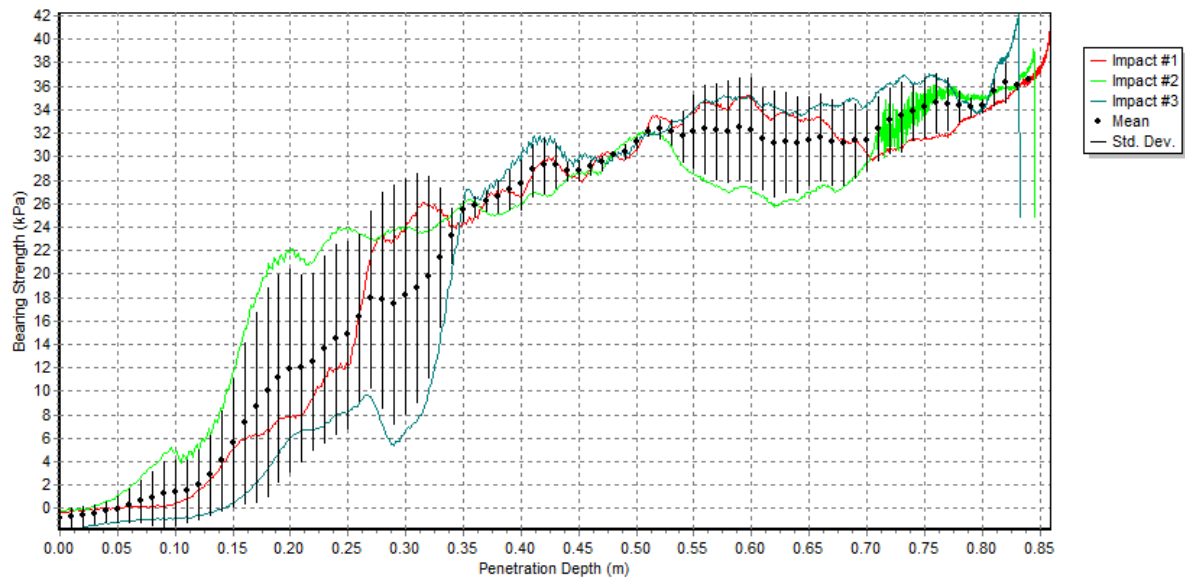
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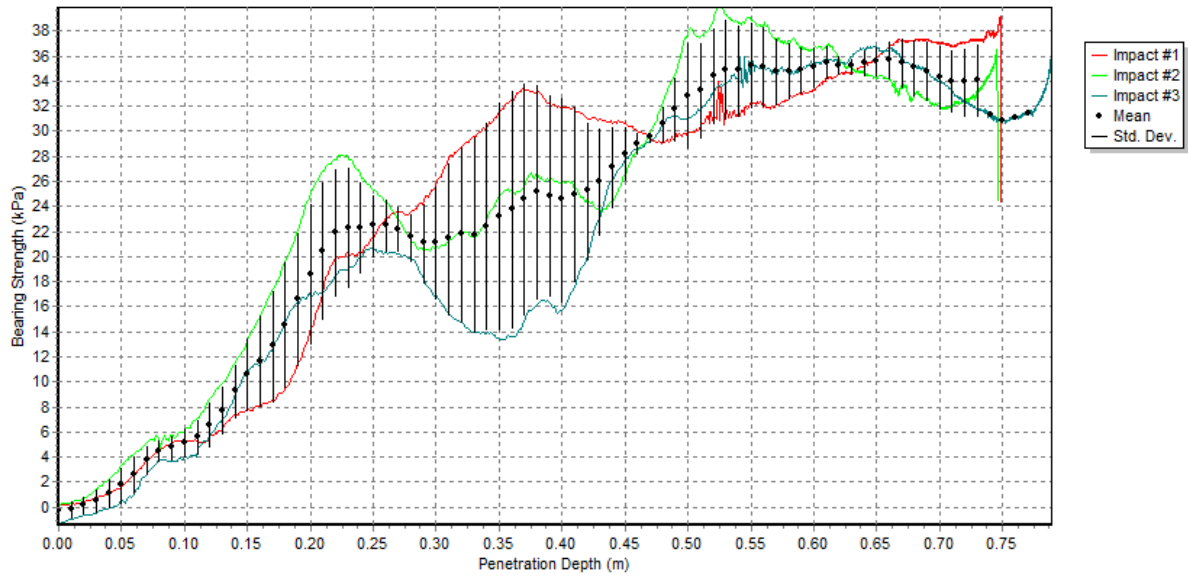
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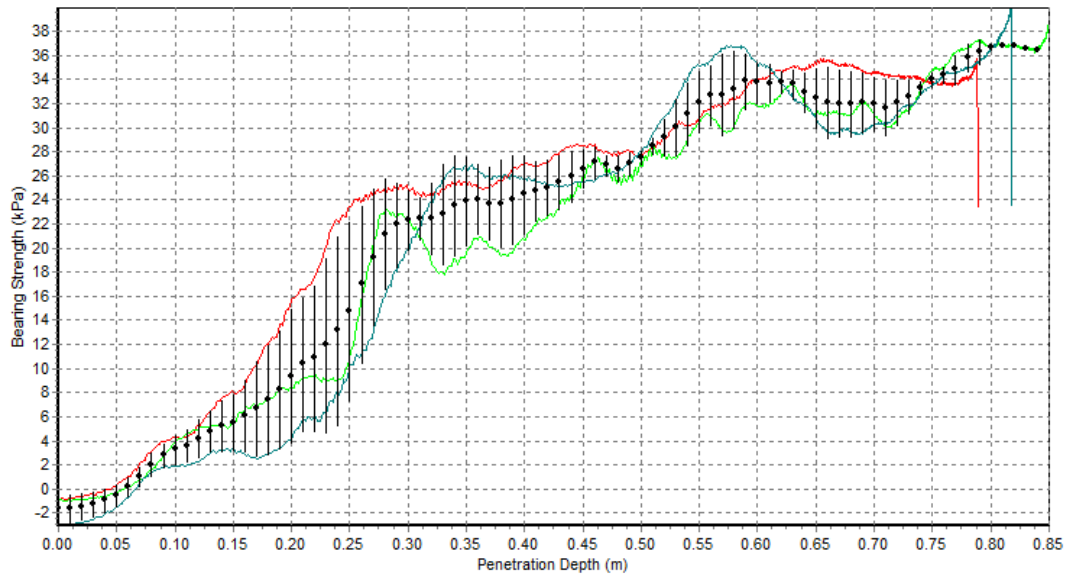
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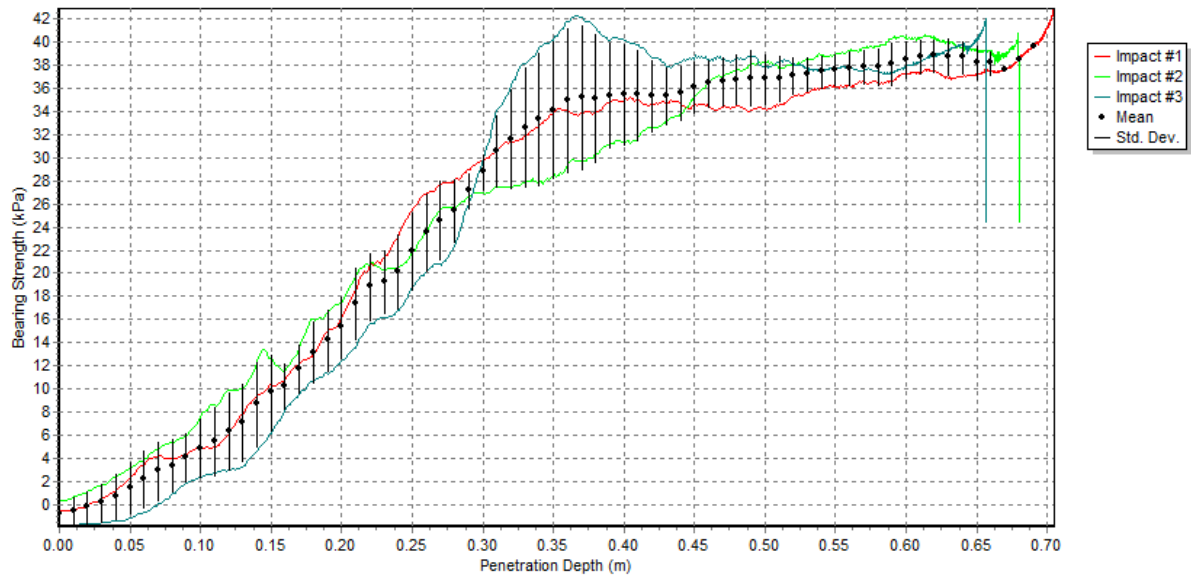
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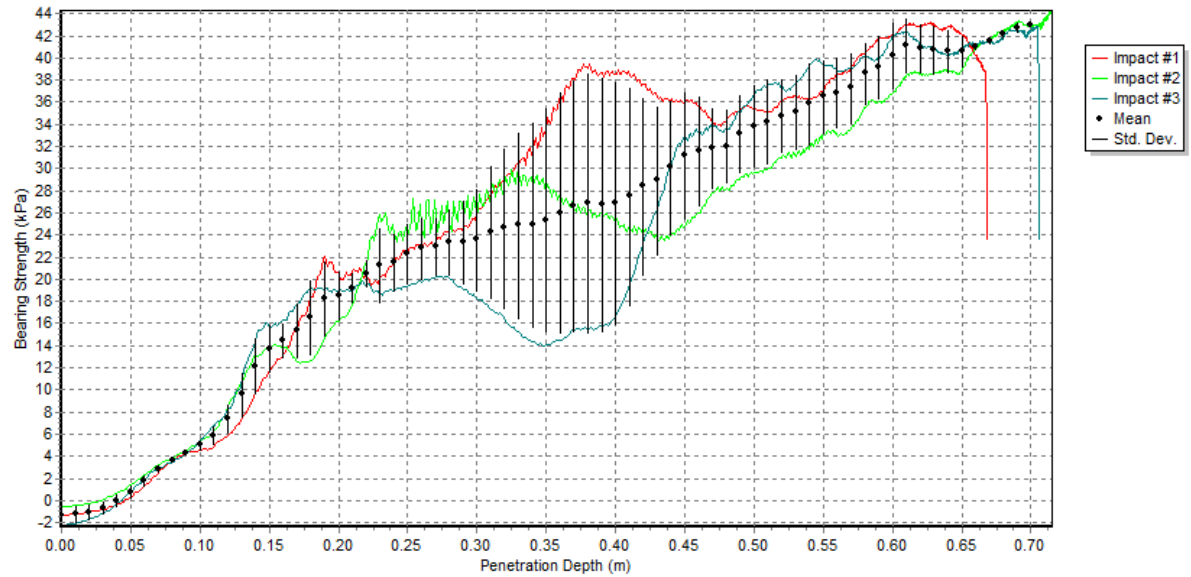
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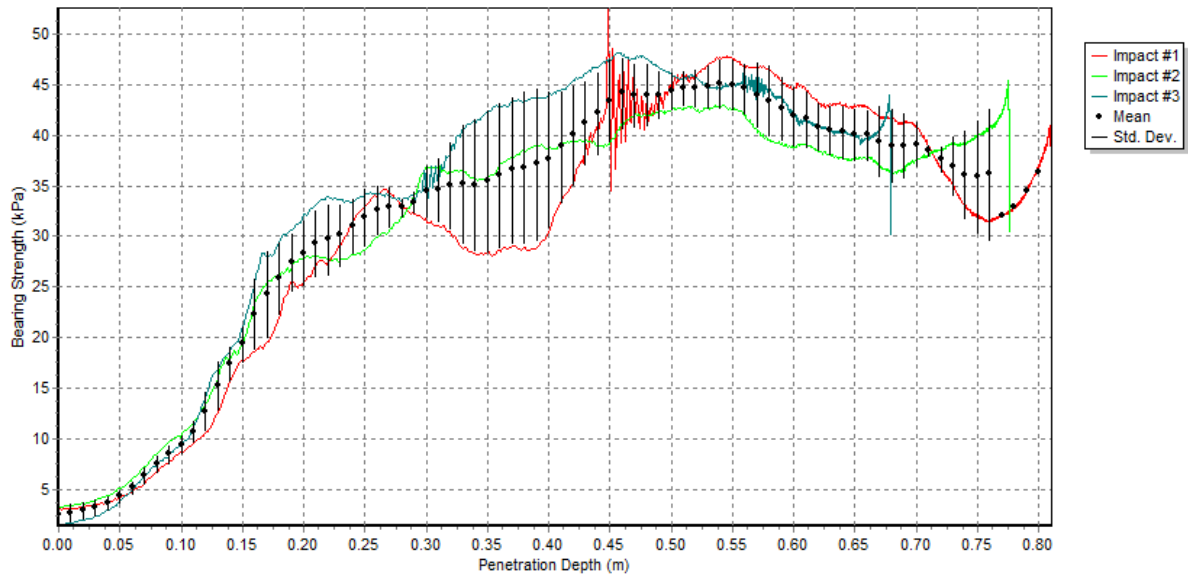
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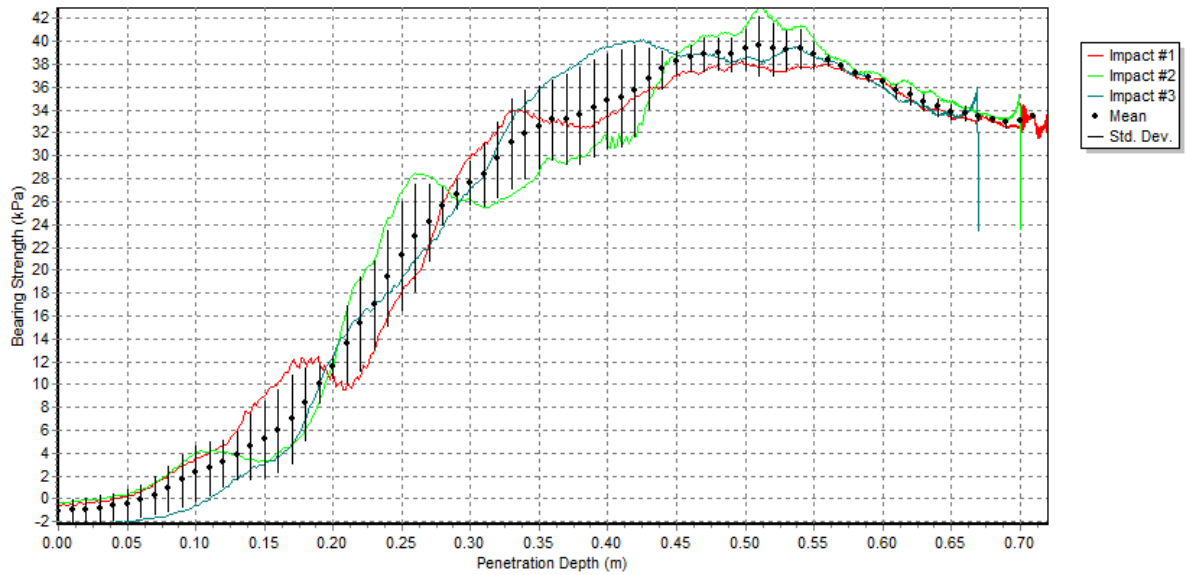
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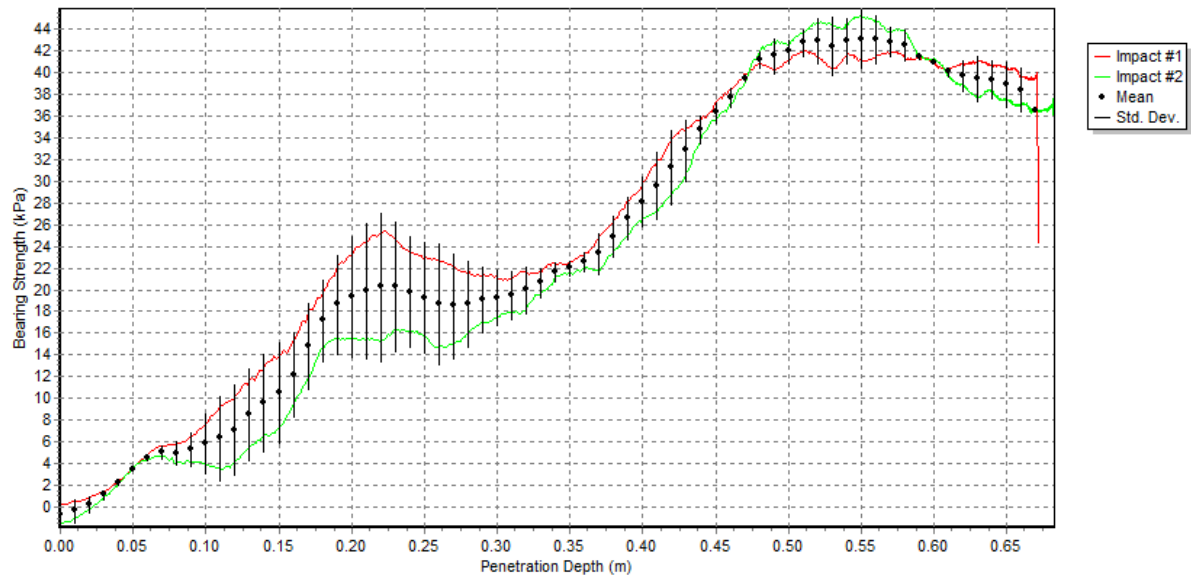
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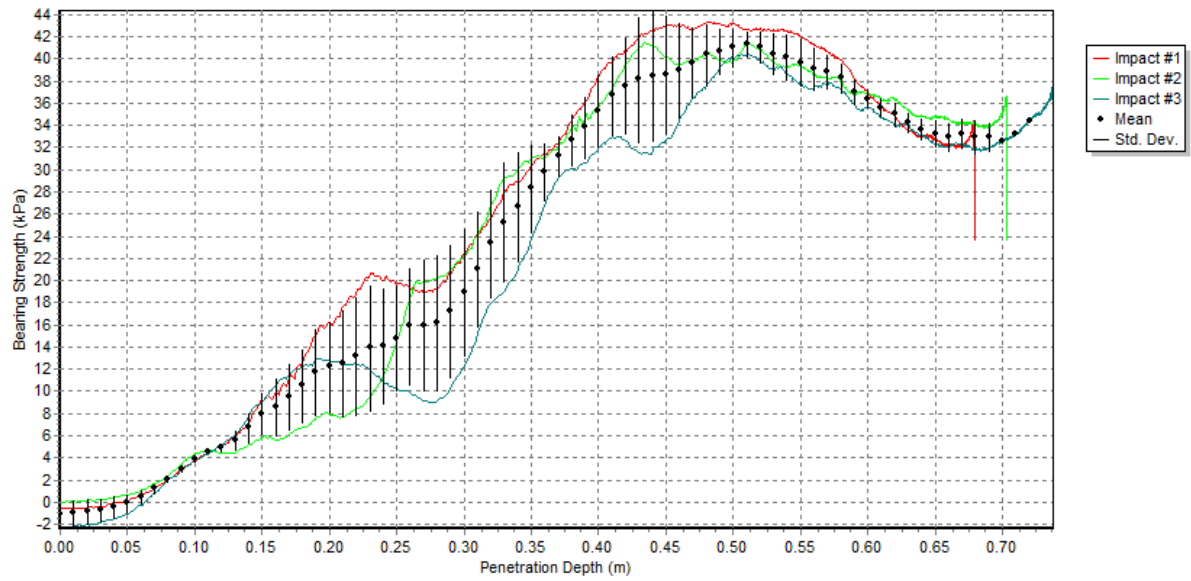
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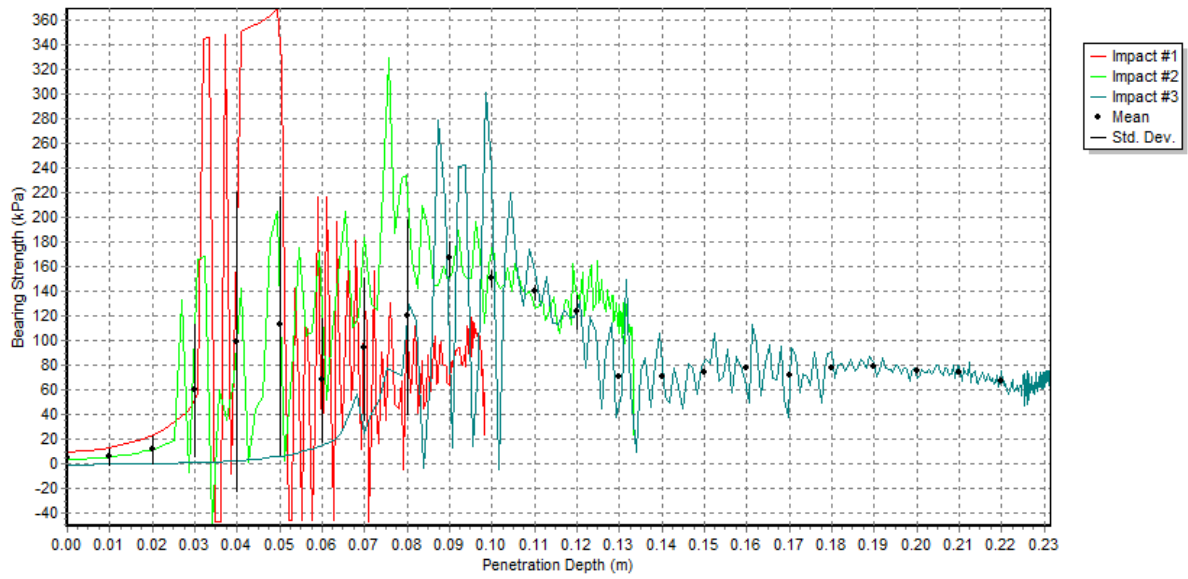
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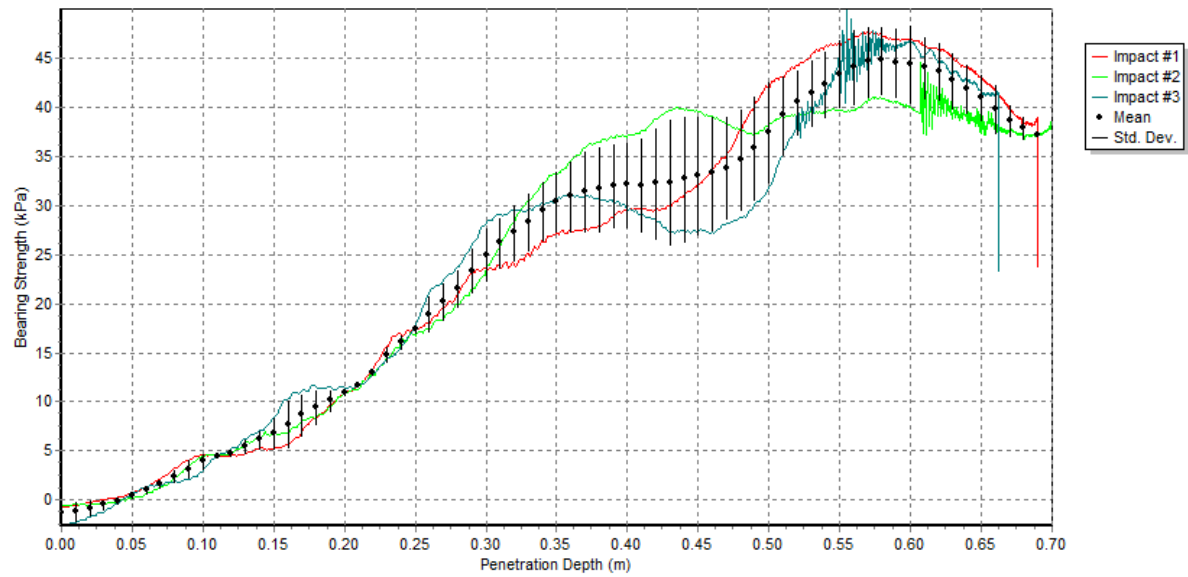
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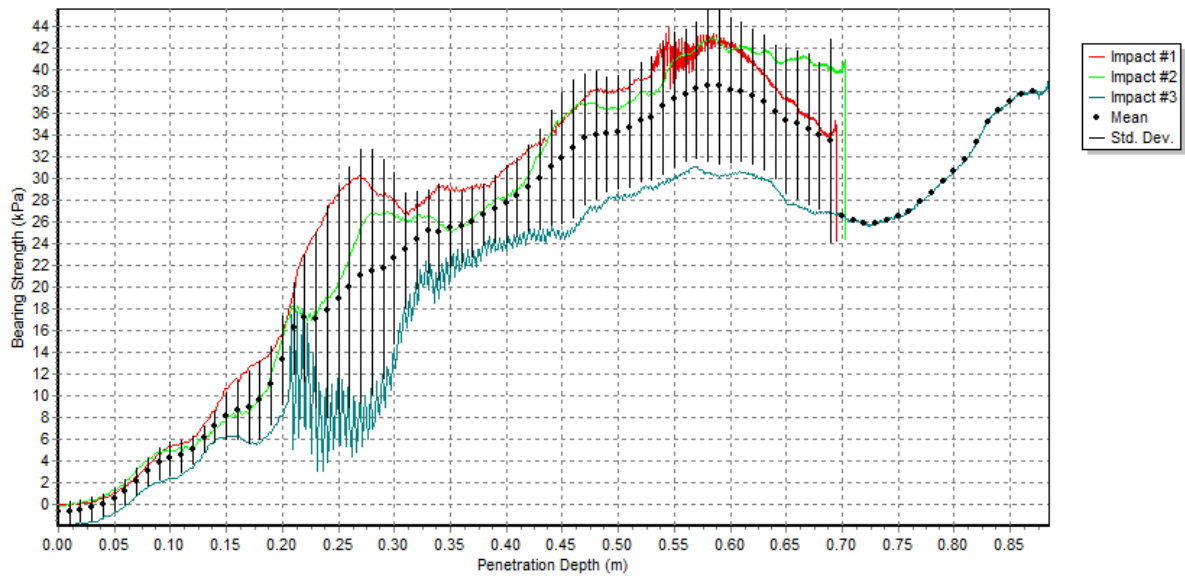
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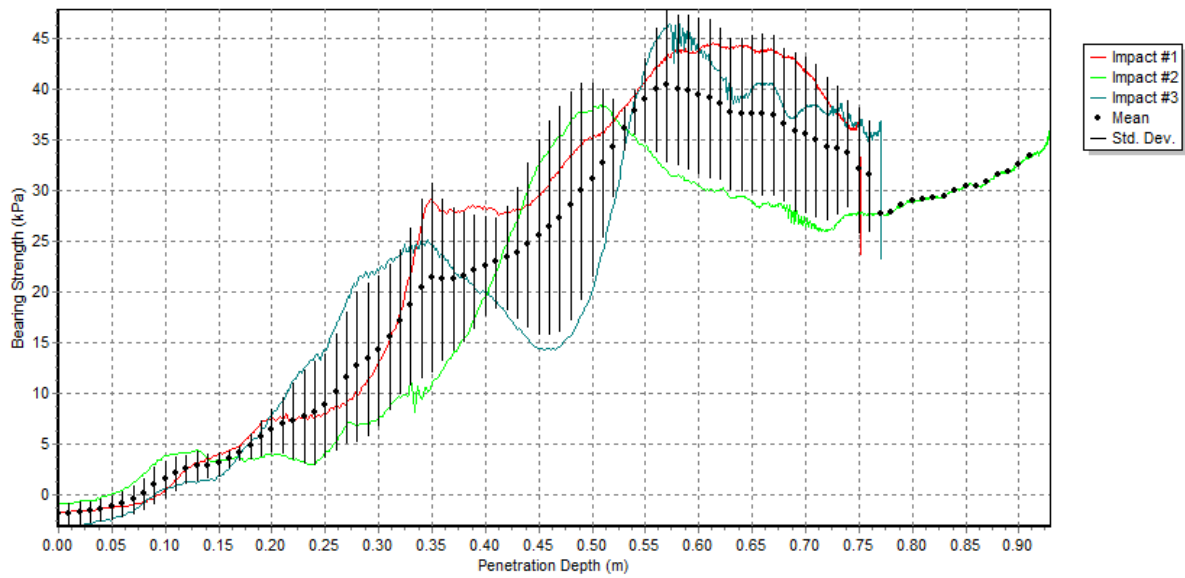
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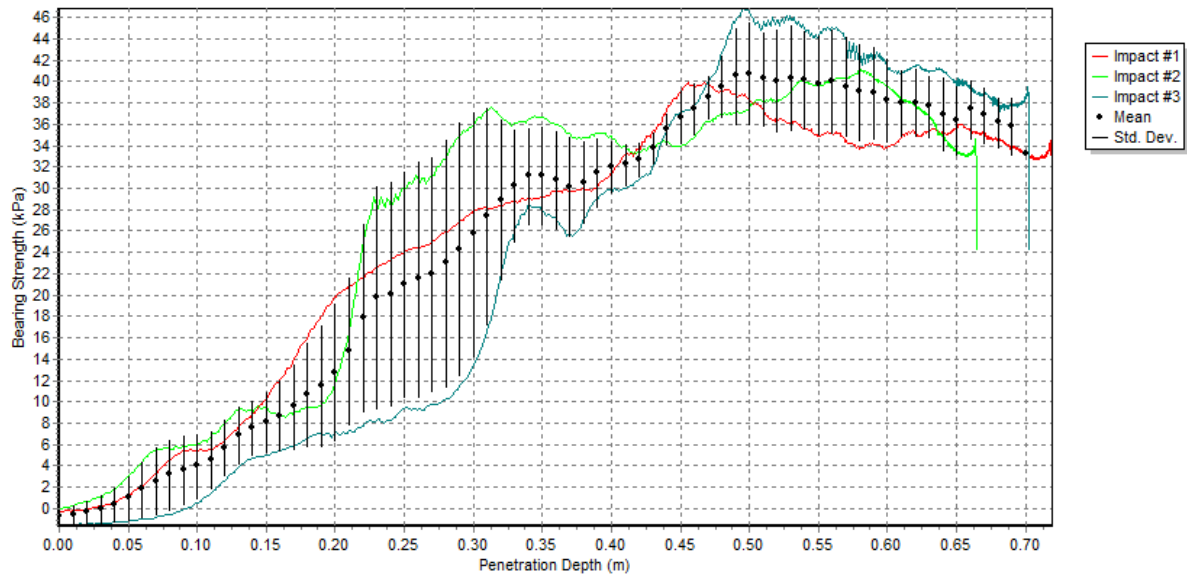
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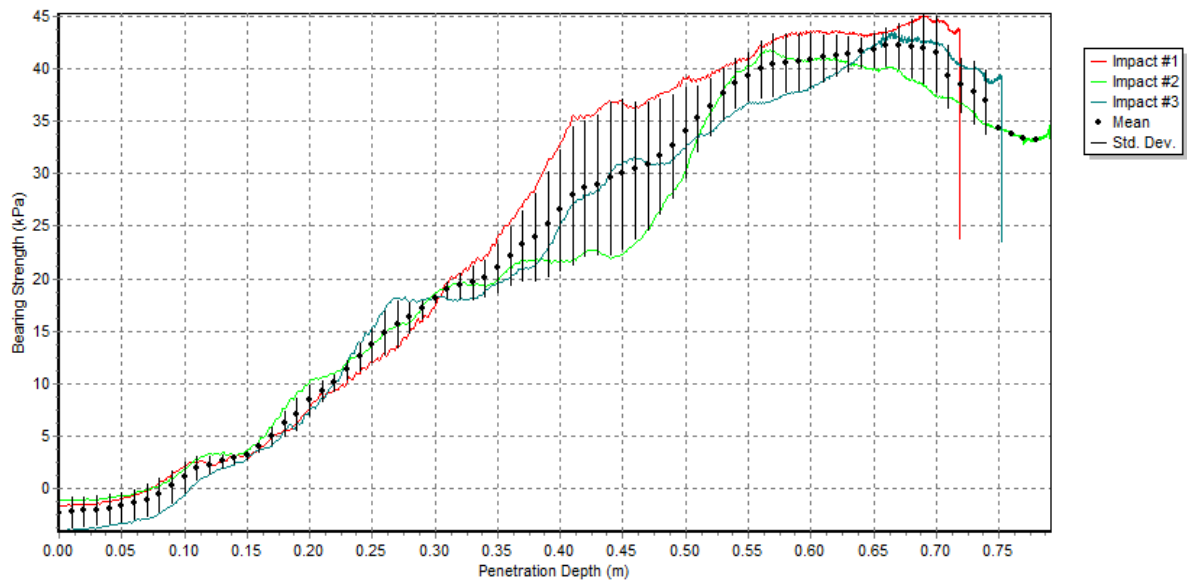
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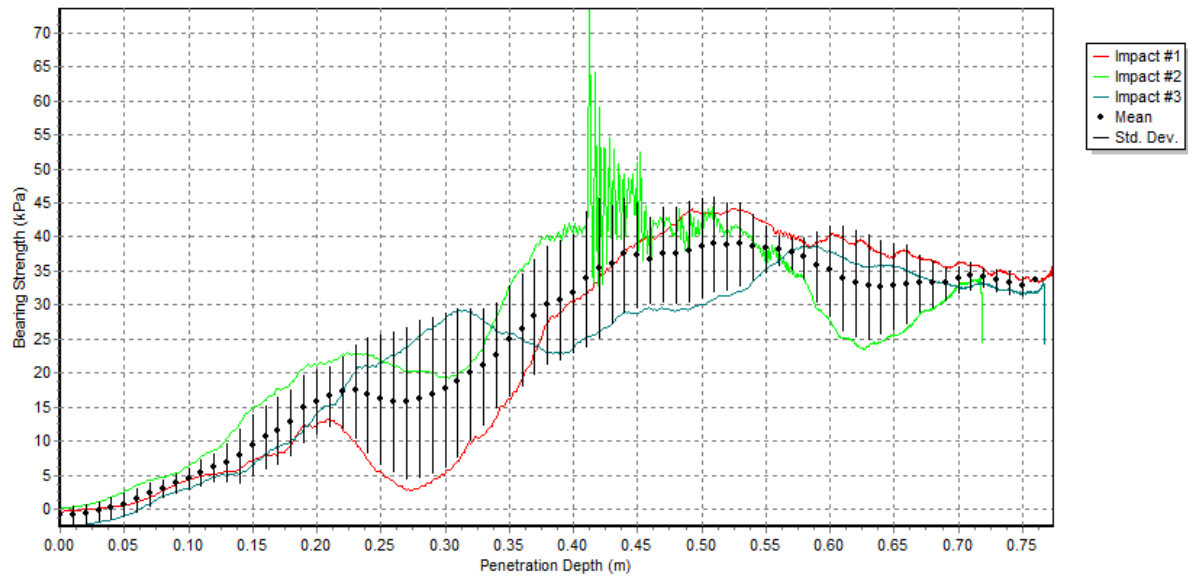
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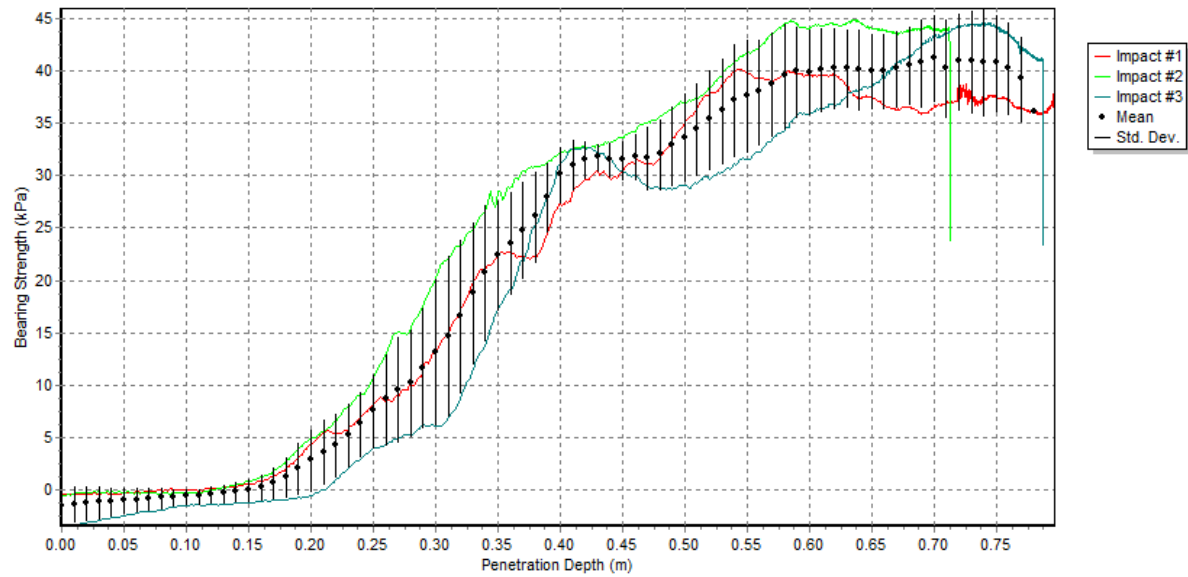
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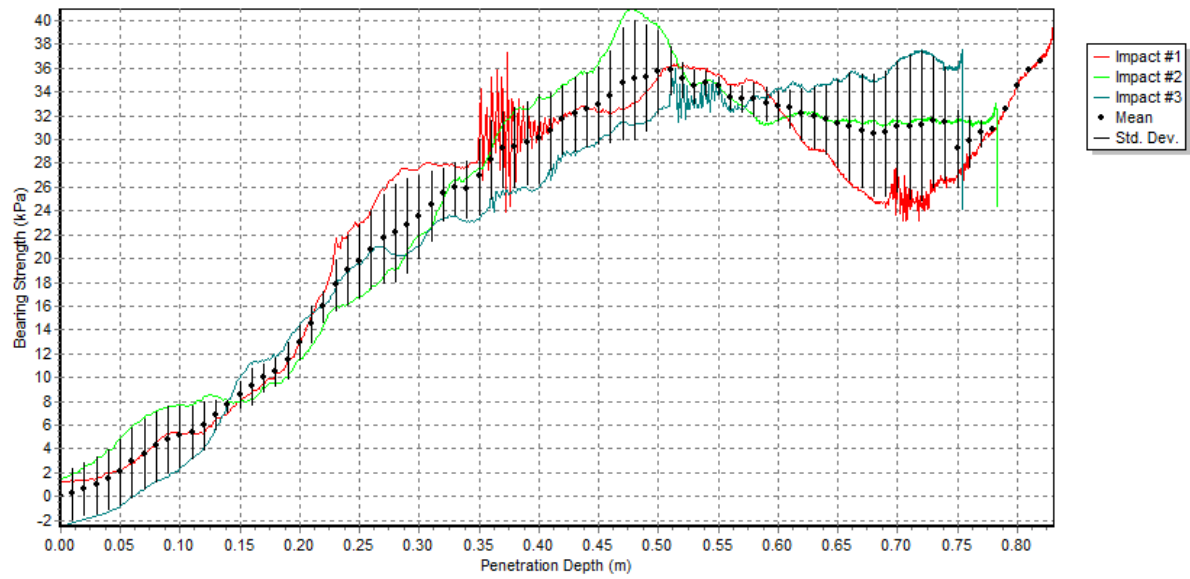
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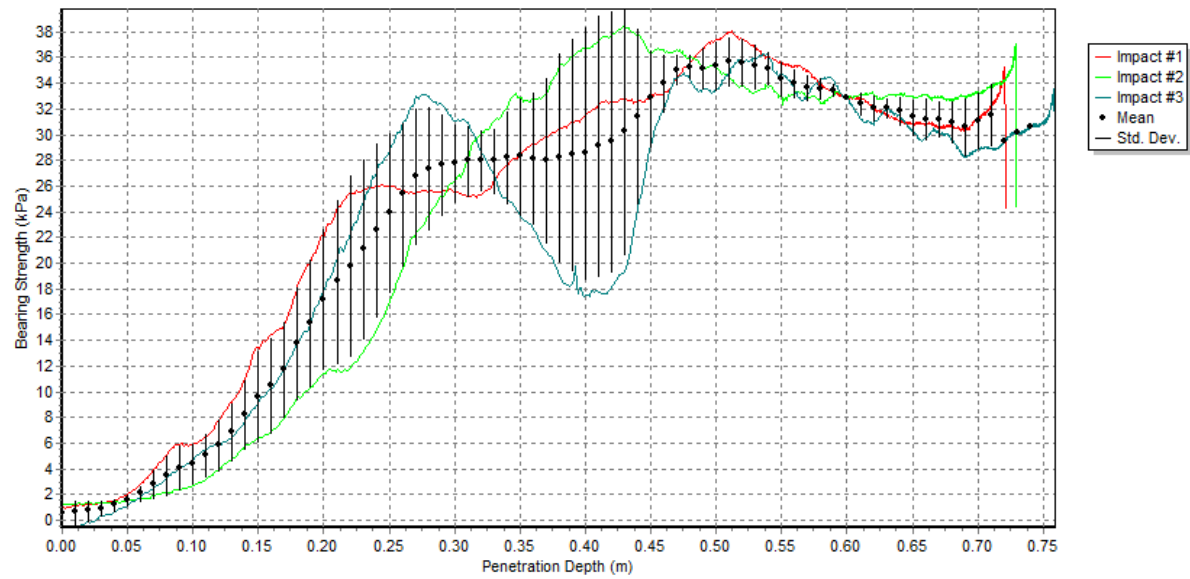
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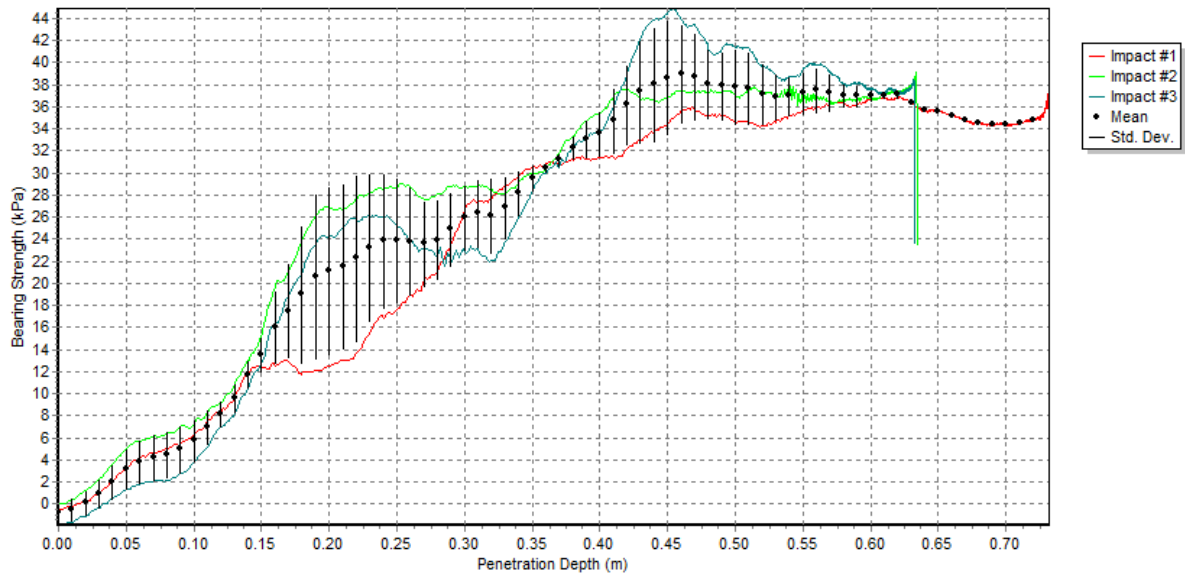
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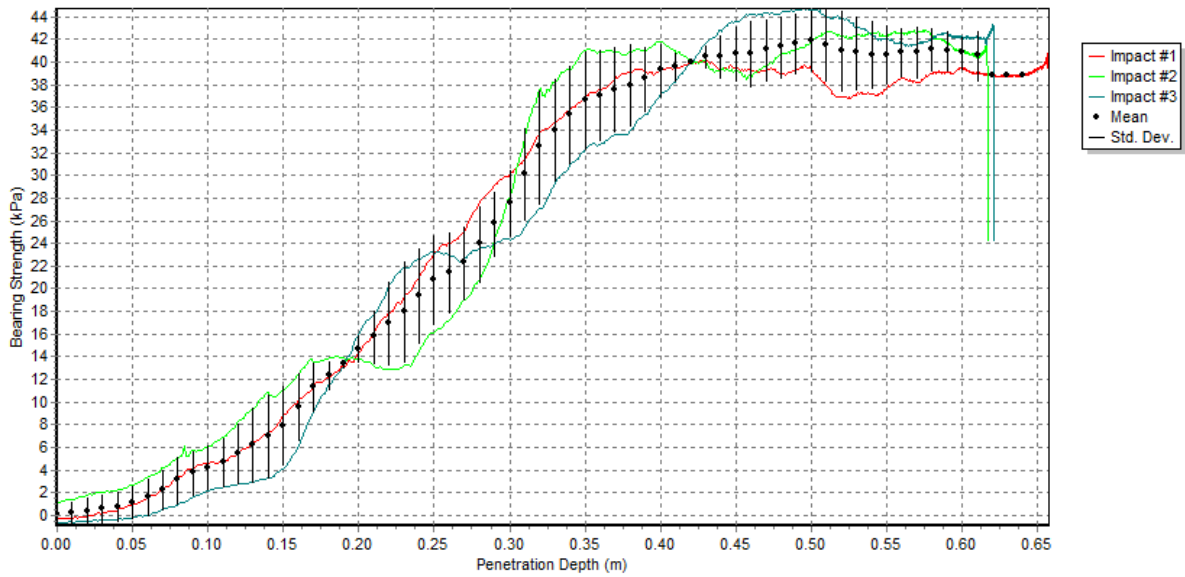
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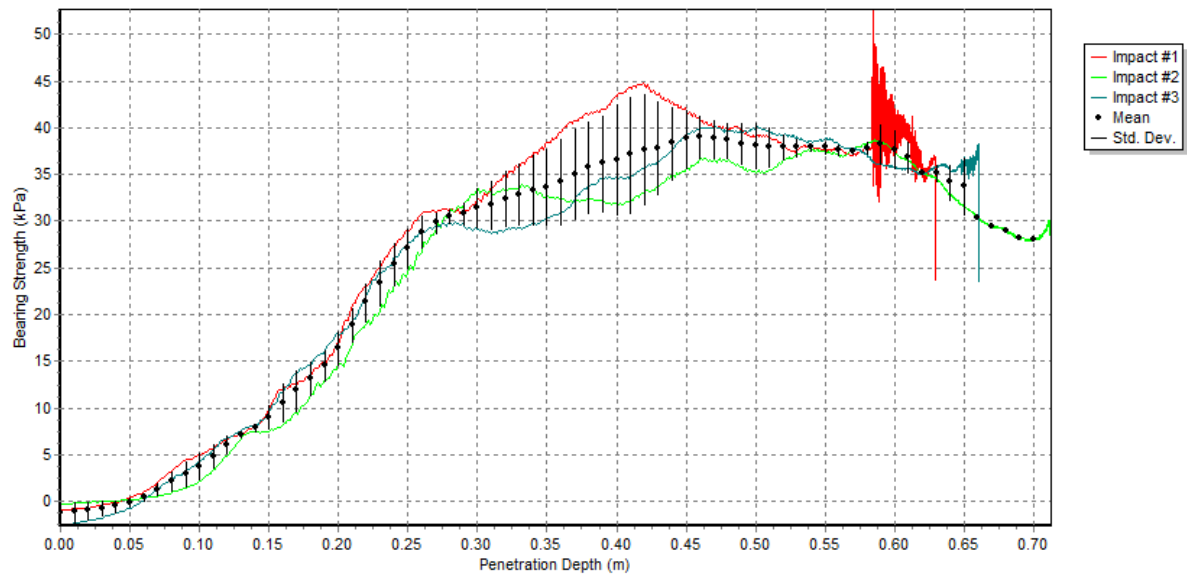
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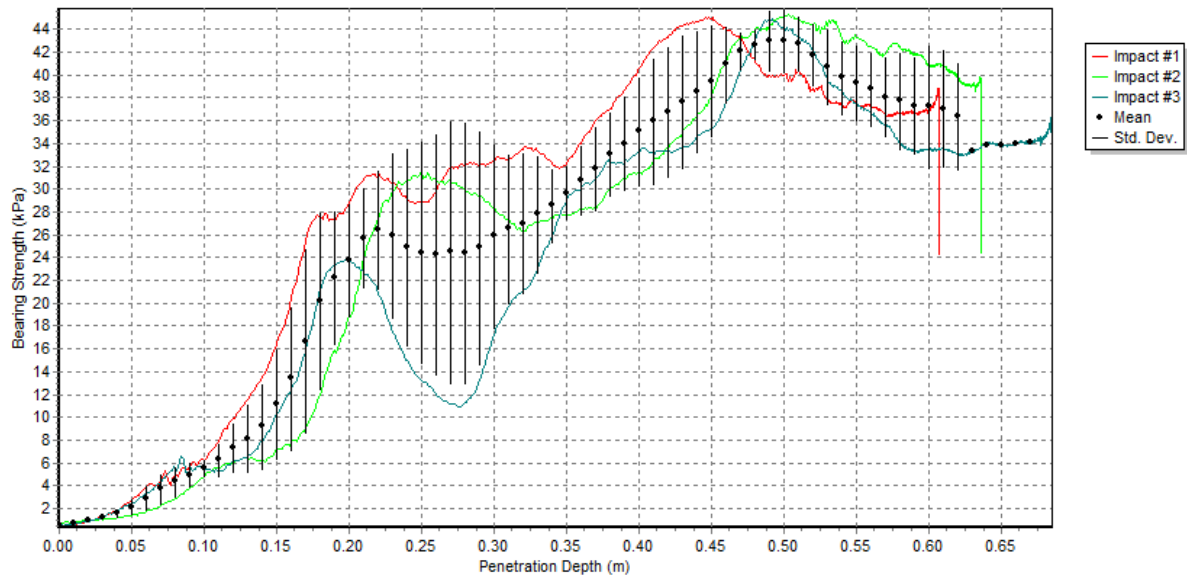
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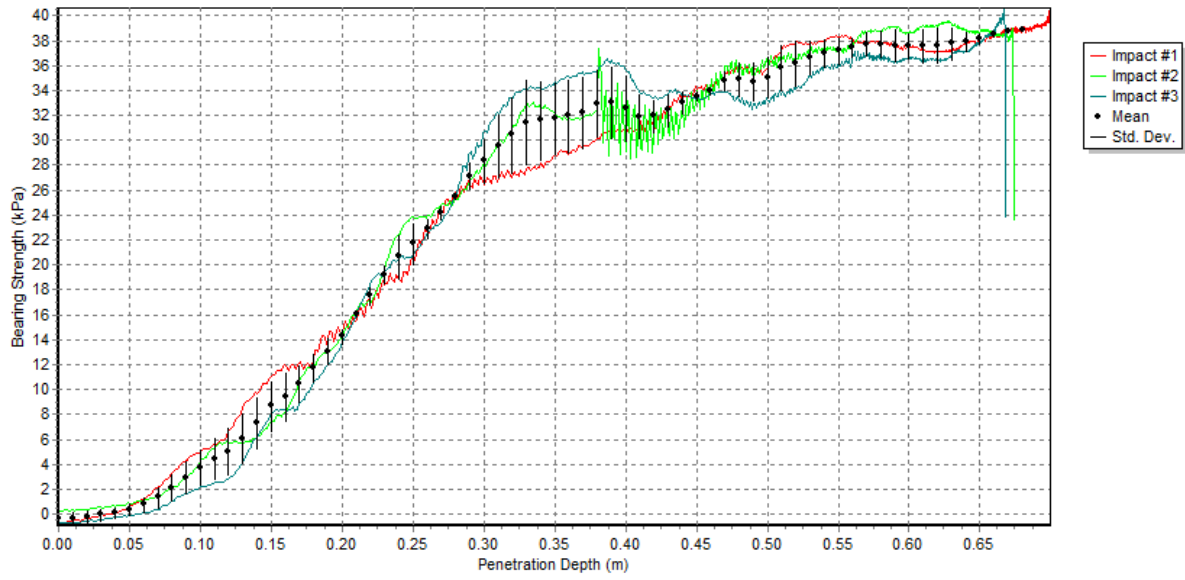
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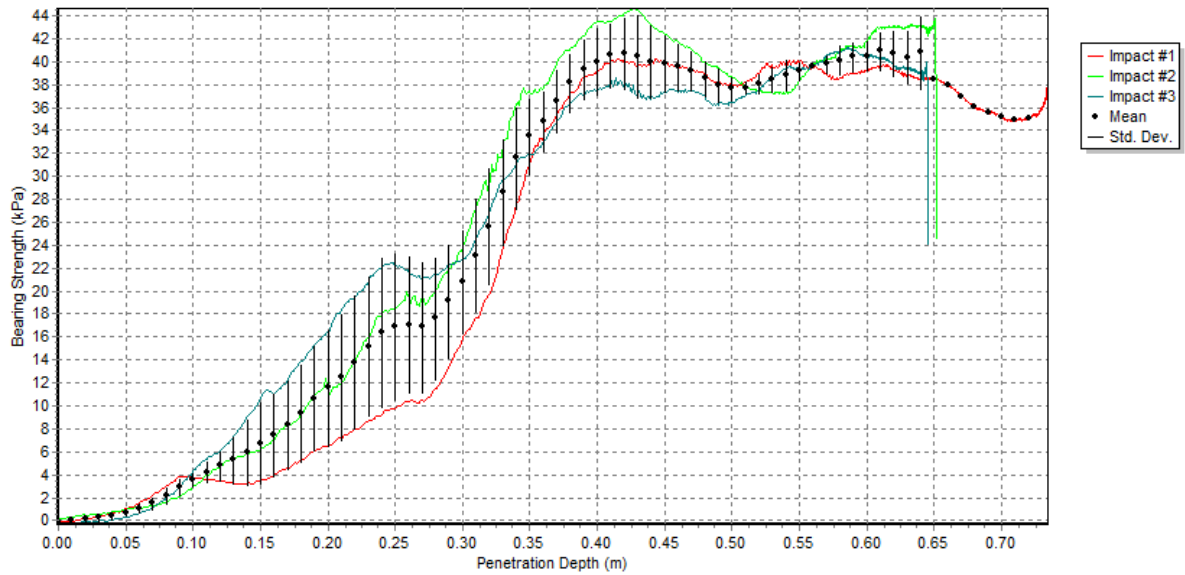
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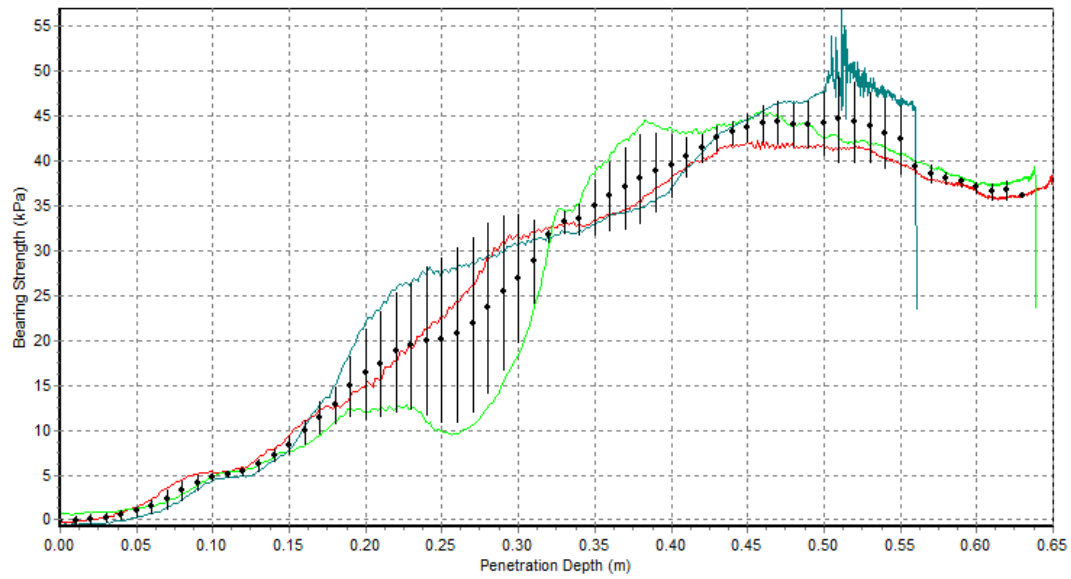
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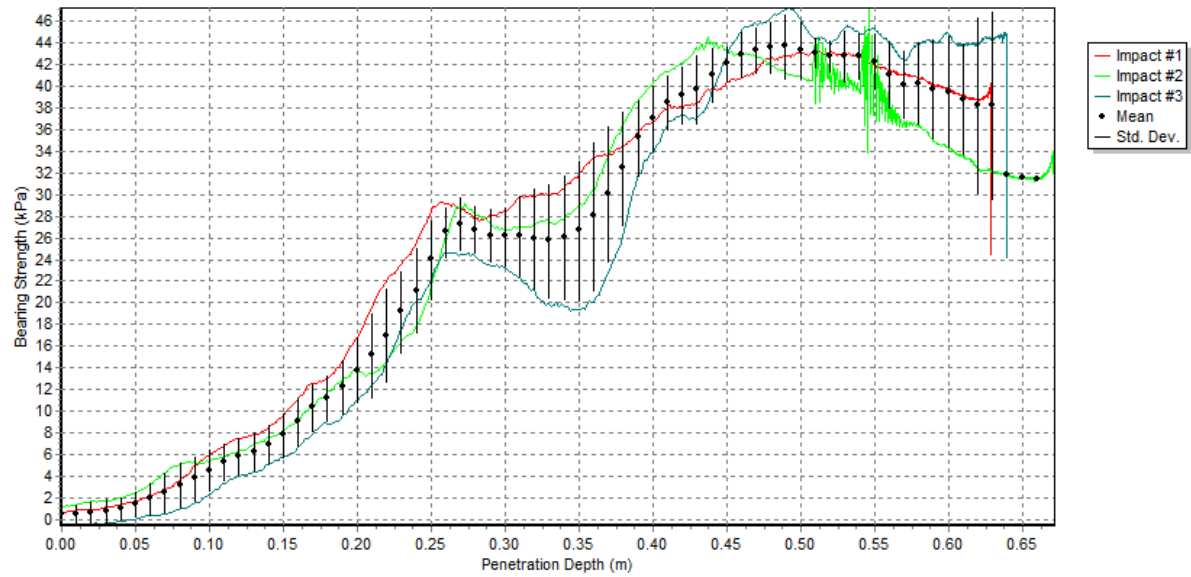
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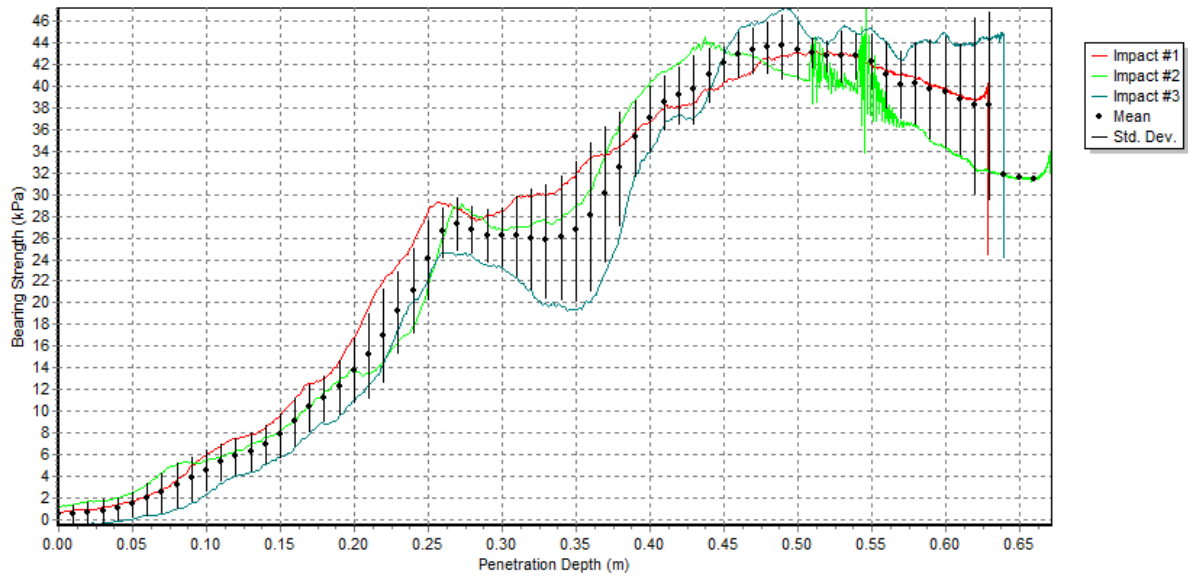
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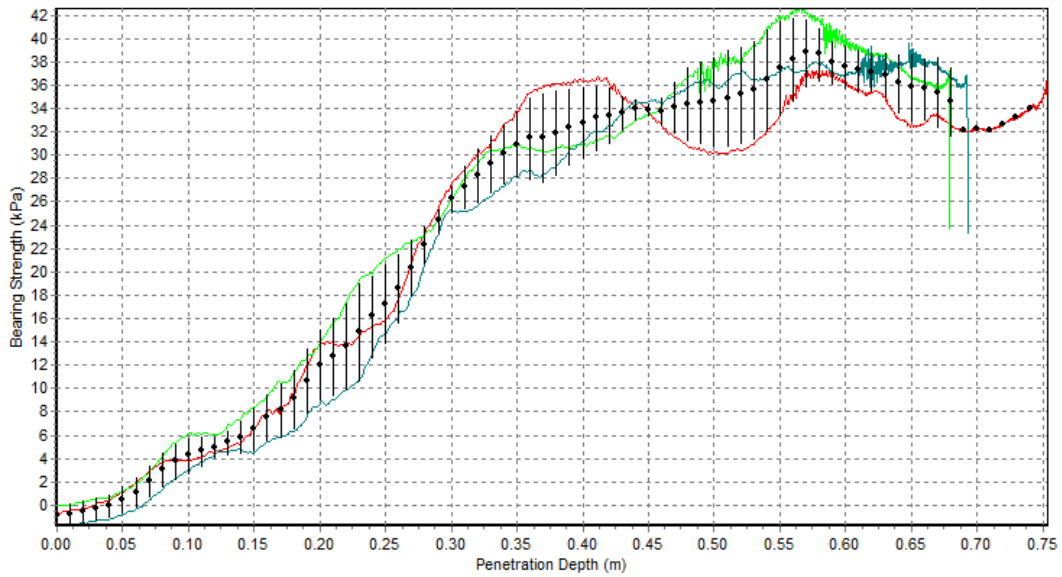
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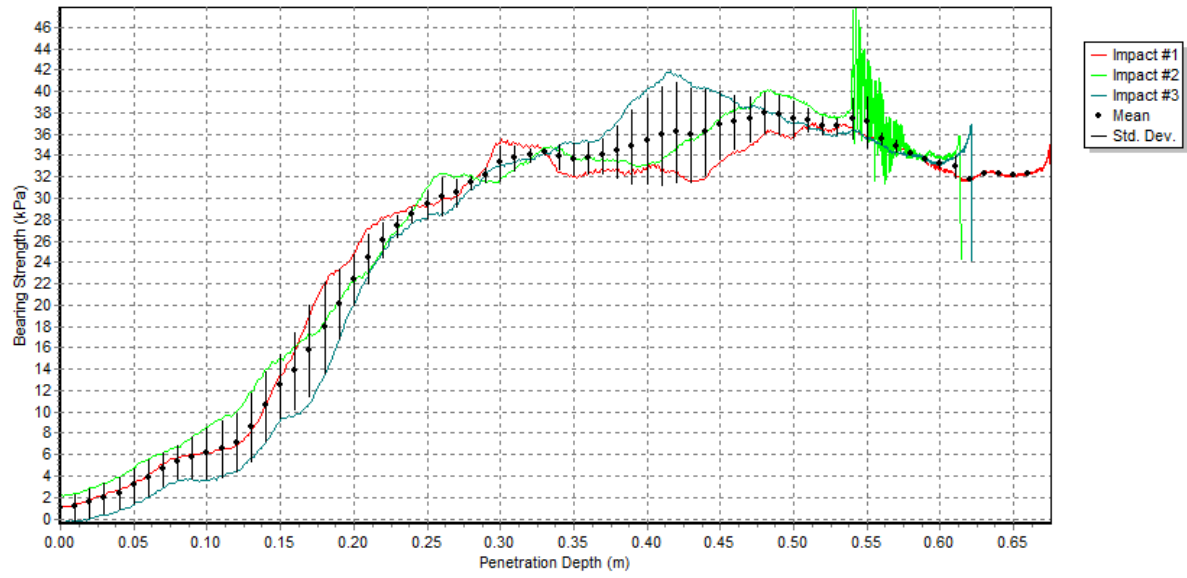
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Station 42:



Station 45:



Station 48:

