A SURVEY SPAR SYSTEM FOR PRECISION OFFSHORE SEAFLOOR SURVEYS

Jeffrey V. Wilson and Dallas J. Meggitt

Civil Engineering Laboratory
Naval Construction Battalion Center
Port Hueneme, CA 93043

ABSTRACT

A new technique has recently been developed and used by the Navy's Civil Engineering Laboratory to precisely survey seafloor positions offshore in diver depths. The system combines a stiff, instrumented spar with conventional high accuracy methods for sighting from shore. The spar is anchored to the seafloor through a universal joint; tilt of the spar is measured in two planes. The position of the bottom of the spar is then calculated relative to the top, translating the surveyed location of the spar top to the seafloor.

With this system two points were established and marked on the seafloor, in 70 feet of water over a mile and a half from the nearest land, to within ± 3.6 inches with respect to First Order survey stations ashore. This represents a major advance in the state-of-the-art of seafloor surveying.

INTRODUCTION

The need to accurately locate positions on the seafloor in the nearshore, diver-depth regime is not new. Moorings, piers, pipelines, cables, tracking ranges, oceanographic instrumentation and more recently offshore oil production facilities all require an accurate knowledge of both geographic and relative locations of points on the seafloor.

Obtaining this data with high confidence requires three basic steps:

1. determination of the location of a point on the sea surfaces
2. establishment of ocean bottom control
3. traverse and profile of the seafloor

Since comprehensive study of seafloor surveying published by Ciani in 1971¹ there have been few changes in technology. Until recently it was still true that the process of establishing ocean bottom control (accurately translating a surveyed surface position to a seafloor position) was in fact "the weak link in this technology".¹ The

Civil Engineering Laboratory, sponsored by the Naval Facilities Engineering Command's (NAVFAC) Chesapeake Division has developed a new technique which significantly improves this process. The concept is simple and extension of the method to other water depths or adaptation to different support craft or surface survey systems should be straight-forward.

SURVEY SPAR PERFORMANCE OBJECTIVES

In the course of a Naval offshore construction project, a method was required to survey (locate and mark) two points of the seafloor in 60 to 80 feet of water, 1 to 2 miles offshore to within ± 6 inches with respect to First Order survey stations ashore.

Standard visual survey methods using theodolites or laser ranging from shore were available for sea surface positioning and divers were available to mark the seafloor control points.

The system was to operate in seas up to Sea State 3 with maximum currents of 1 knot. The system was to be handled from a moored 280 foot barge, the Ocean Construction Platform (OCP) SEACON.

DESIGN APPROACH

Plumb-line techniques were rejected because the natural resonant period of 60-70 ft lines coincides with ship and wave motion periods and because physical positioning of a ship and crane to within ± 6 inches is not feasible. Underwater lasers likewise have not been developed to accuracies of better than about ± 2 ft at this depth in the ocean. Conventional sonar systems are accurate to only about ± 1 ft at the necessary ranges and depths.

Instead it was decided to use a rigid structure, attached to the seafloor and penetrating the surface. Because of the water depth a fixed tower would be very expensive to build and use. The choice was therefore to use a stiff, straight structure which could pivot about an anchor on the seafloor. The location of the bottom with respect to the top could then be accurately determined by measuring the tilt of the structure and computing the offset of the bottom relative to the

top. This approach leads to a concept similar to the spar buoy in a taut moor or to the rigid single-point moors used for offshore tankers. The structure utilizes its internal buoyancy to remain erect and stable while the weight of the anchor keeps it in place on the seafloor.

In operation, the top of the spar is tracked by the shore survey stations while the tilt of the spar is continuously monitored by an instrumentation system. Simultaneous readings of the survey instruments and tilt indicators allow direct determination of the anchor location relative to the shore. With several repetitions a statistical spread could be obtained and the mean anchor position determined. Since the bottom was not moving the readings should all be identical and any variation would be a direct indication of combined random errors.

SPAR STRUCTURAL DESIGN

The general configuration of the spar designed for this application is shown in Figure 1.

Figure 1. Survey spar system.

The main body of the spar has three primary design constraints:

1. It must be stiff enough to closely approximate a straight line in the presence of bending forces from current drag and wave action,
2. It must be strong enough to be handled both vertically and horizontally ashore and at sea,
3. It must have a proper weight-to-displacement ratio to allow substantial in-water weight when flooded but at least a neutral buoyancy when fully de-watered.

For the 65 foot length of interest in the NAVFAC application these requirements were met by a choice of 8 inch diameter schedule 40 aluminum pipe. If the spar is constrained at the top by the moored ship and at the bottom by its anchor base in the presence of a current profile varying from 1 kt at the surface to 0.5 kt on the bottom the pipe will bend approximately .35 inches at the center. For this geometry the error introduced by the bending is only about 1.4 inches.

The 60 ft pipe weighs 600 lbs in air and has a buoyancy of 980 lbs when de-watered but submerged. The spar was built in three 20-ft sections with flanged connections to allow disassembly for shipping. Thin gaskets were used to limit flexure at the joints. The unit was aligned and bolted together horizontally and then welded in assembly. The distortion which did occur was less than an inch and was zeroed out during instrumentation calibration. Since the spar was free-flooded through vent holes at the bottom the maximum pressure differential at any seal would be about 40 feet of seawater (18 psi) at the upper joint.

The bottom of the spar was bolted to the instrumentation package, which was also constructed of 8-inch aluminum pipe. The anchor was attached by a commercial universal joint to the bottom of the instrumentation package.

ANCHOR DESIGN

The anchor served two purposes in this application:

1. It provided the minimum in-water weight needed to ensure that the spar did not drag laterally in the presence of currents and waves,
2. It served as a template for driving marker stakes to physically define the datum once it had been established.

In a linear current profile of from 1.0 kt at the surface to 0.5 kt at the bottom there will be a total of 91 lbs drag on the spar system with about 70% of the load being carried by the tether at the top when the spar is vertical. If the spar were left free to assume its natural angle of tilt in the current, the anchor would have to resist the entire lateral load. In any event the anchor

would not have to resist more than the total 91 lbs load. Since a clump anchor will resist side loads equal to about half of its own in-water weight, the entire anchor and spar assembly needs to weigh only about 182 lbs to resist sliding. Because of motions caused by wave action it is prudent to provide a safety factor; anchor weight of 250 lbs wet (400 dry) was determined to be sufficient so that if the spar is launched and allowed to flood naturally it will settle to the bottom with enough net weight to hold it in place. Once fully flooded it has a safety factor of almost 9 over any expected drag forces. A photograph of the spar anchor is shown in Figure 2.

Figure 2. Survey spar base assembly.

The anchor construction is designed to keep it as low as possible so that the spar pivot point is close to the bottom. However, the clearances required to allow the spar to lay down horizontally mean that the universal joint is about 18 inches above the bottom. Correction for the fact that this point (the computed bottom of the spar) may not in fact be directly above the center of the anchor if the bottom is not level is discussed in the section on errors.

MAST DESIGN

The mast is the portion of the spar which projects above the water and provides the visual target for the survey from shore. It should be as light as

possible to reduce the overturning moment on the spar but must be straight, rigid and strong enough to tolerate handling. In some cases the spar is actually tended from the mast so the mast must withstand bending moments caused by current drag. In the NAVFAC application the mast was to extend 20 feet above the water at the shallowest depth, at low tide. With about 5 to 10 feet allowed for bottom depth and tide variations the spar should still be clearly seen over the main deck of the support vessel. Calculations indicated that a 4 inch schedule 40 aluminum pipe would meet all of the requirements. It weighs only 110 lbs in air with its mounting flange and in the presence of the full current profile, tended at its midpoint, would bend about 0.2 inches.

INSTRUMENTATION AND CALIBRATION

Three sensors are mounted in an 8-inch aluminum pipe housing at the base of the spar. These are a solid state flux gate compass and two resistive element wire-wound potentiometers for measuring 2 axis tilt. The two potentiometers are oriented 90° with respect to each other. The maximum resolution is the diameter of one winding of the resistive element of 0.07°. The deadband is measured at .2°.

An eight wire cable is used to furnish power to and transmit the signal from the underwater package through an Electro water-proof connector.

The readout package is on deck. It furnishes DC power to operate the sensors and displays the digital data received. Appropriate controls allow for the calibration check of the flux gate compass and to freeze the readings on command. Analog meters are also provided to give an overall view of the data.

The entire system is zeroed and calibrated by actually erecting the spar on land and stabilizing the top with adjustable guywires as shown in Figure 3. A plumb bob is suspended from the center of the top plate hanging freely inside the pipe and viewed through the flood/vent holes in the bottom. By adjusting the guys to center the bob and then zeroing the tilt indicators it can be established that the top of the spar is vertically over the base, regardless of any curvature in the pipe. In practice this could easily be repeated to within +1 inch, despite some swaying of the bob caused by the guys or spar movement in the wind. This was done both before and after the survey operation. No change was found.

The sign conventions and general magnitude of the sensor readings may be checked by leaning the spar in various directions, computing its movement from instrument readings and then comparing that with movement of the shadow of the spar top for displacement of a few feet or the bob inside the pipe for displacements of a few inches.

The compass is checked by visually comparing the external orientation reference work heading with

the compass reading.

Figure 3. Survey spar erected for calibration.

SPAR OPERATIONS

The spar system was assembled and calibrated on land at CEL. The unit was also taken to sea and handled over the side of a moored Warping Tug. During these tests at sea the ballast control system worked well and on a calm day the spar could easily be lifted and suspended off the bottom within ± 1 foot with the air system. Divers were able to move the SSA around on the bottom anywhere within about 10 feet of its nominal position. With the spar just resting on the bottom divers were able to lift it and move it around by walking. The net change in in-water weight is about 25 lbs per foot.

The unit was disassembled and shipped by truck to the work site, where it was reassembled and again calibrated. In this case it was erected on the pier where the ship was berthed so it

could be lifted directly aboard after calibration.

The spar was loaded aboard and laid horizontally on deck. The ship transited to the site and moored within about 10 feet of the first survey site.

Two large pipes were lashed in place as outriggers for steadying lines to hold the spar away from the stern and a small 5-ton crane was used.

While the spar is awkward because of its height, it is not heavy and steadying lines top and bottom were ample to control it, even in winds to 20 kt and 5-6 ft seas. Once the spar was installed, divers staked the bottom while sights were taken. The shore survey used WILD T-2 1-second theodolites, triangulating on National Geodetic Survey first order stations at three points on the beach, with various other points used for azimuth control. A K&E ranger laser system was also used to take a single range on the mast as a general check and confirmation. On radio command from the control station all operators stopped tracking the mast and recorded the angular readings. At the same command NAVFAC personnel on the ship pushed a HOLD button to freeze the tilt indications on the spar.

For each sighting the surveyors converted their readings into a position of the mast top in a local grid system and reported it to the spar system operators aboard ship. This position and the tilt and heading of the spar were used to determine the projection of the spar on the seafloor and resultant offset position of the base swivel point. Diver reports of the tilt of the anchor were used to estimate the additional offset of the anchor center and the computed position was logged. This process was repeated 8 times and the mean was determined.

The first set of sightings was very consistent, with all the shore sightings closing to within about 2 inches. The final bottom position had an estimated standard deviation of about 3.6 inches. Stakes were driven, the spar was floated free and the final stake was located in the center, offset about 2 inches to account for the 8.5° tilt observed on the anchor.

During this first operation it was discovered that the spar could be handled in currents up to 1.2 kt by attaching the lift line about $2/3$ of the way up from the bottom. When the spar was lifted and suspended in the water column the drag above and below that point was about equal so the spar hung nearly vertically. This allowed adjustment of the spar location from the surface with very little diver assistance. The entire operation took about three hours elapsed time.

The spar remained anchored to on the bottom overnight; the next morning the ship warped to the next intended position with the spar floating from the stern.

The first sightings indicated that the anchor had

been placed 24.5 feet away from the intended position. Final sightings indicated that the anchor was within 8 inches of the intended position and only 1.8 inches off of the intended line between the two points. The entire operation for this set of sights took four hours.

ERROR ANALYSIS

Table 1 outlines the various error sources in the survey spar system and provides estimated values as well as observed totals. One advantage to the spar system is that if readings are taken with the spar leaning at various headings and in different currents it is possible to factor out all of the known systematic errors and have a good statistical base for determining the magnitude of the random errors.

1. Mast. The mast must be installed vertically on top of the spar and must not bend during handling. In general the fixed alignment can be held to within about ± 1 inch and will not vary during the operation. Under forces associated with the design current the mast bend will yield about a 0.8 inch error.

2. Spar. The spar is calibrated on land to eliminate all the bends and offsets introduced during fabrication and assembly so the only error here is that caused by the spar bending away from its calibrated "straight line" shape. The design current causes a maximum bend of about 0.35 inches at the center, for a maximum error of about 1.4 inches. Note that in applications using a longer or thinner spar a first order correction could be applied to reduce some of this error if the

Table 1. Survey Spar Errors (Random)

EFFECT	ESTIMATED VALUE	SENSITIVE TO
Mast top with respect to shore	± 2 inches at 1 to 2 nm, on a clear day, 3 stations with good angles, from First Order points (should generally be at least as good as 1:10,000)	range to shore, visibility, angles, quality of shore ref. grid, mast motion
Spar/Mast variation from	mast ± 0.8 in (max) spar ± 1.4 in (max) (1 kt/0.5 kt current)	current, waves
Instrumentation	inclinometers ± 0.10 (2 in at 80 ft) compass $\pm 1/20^\circ$ (1 in per 10 ft)	spar length, spar vibration major magnetic objects on bottom, local variation
SSA tilt measurement	± 0.3 in (assumes 10° tilt measurement error)	diver reading error

estimated spar error ± 3.3 inches

estimated shore survey error ± 2.0 inches

estimated total error ± 3.9 inches

(observed total error ± 3.6 to ± 2.7 inches)

The error sources fall into two groups: those associated with the survey from shore to the mast top and those involved with the spar itself. The survey from shore can be accomplished in many ways and in general will be different for each case. The basic principles of land surveying are well understood but extra care must be taken because of the "seeing" effects over water. The final desired accuracy of the survey will dictate the method chosen. The principal contribution of the Survey Spar concept is that it enables the surface position to be translated to the seafloor with very little loss of accuracy.

The errors, (Table 1) from top to bottom, are as follows:

current direction and magnitude are known. It is possible to estimate this deflection within 10 to 20%, which for a reasonably rigid spar should keep the random error within an inch or so.

3. Instrumentation. Commercial inclinometers were used which had a resolution of about 1.00° and the flux gate compass was accurate to about $1/20^\circ$. The compass accuracy was important only if the spar was tilted substantially so that its projection on the seafloor was over a few feet long. If that occurred errors in heading would produce errors in computed position of 1 inch per each 10 feet of offset. Calibration tests on land showed that the system was sufficiently sensitive to resolve about a 1 inch move-

ment and was reproduceable to about 1 inch. Combining that with possible errors in signal transmission up the cable and display yielded an estimated error of about ± 2 inches.

4. Anchor Tilt. Because of bottom irregularities the center of the anchor may not be exactly below the swivel. The maximum error in this design would be 2 inches. With simple measurement of the tilt on two axes by divers with a calibrated pendulum the error was reduced to about 0.3 inches.

Taking the square root of the sum of the squares of these errors produces an estimated total error for the spar system of ± 3.3 inches, with a confidence level of about 90%. Since the observed errors of the shore survey were about ± 2 inches this would give a combined estimate of ± 3.9 inches. In actual practice the sightings at one end were grouped so that the standard deviation was 3.6 inches and at the other end the standard deviation was 2.7 inches. As a final check a carefully calibrated line under a measured tension was strung between the two driven references on the bottom for further seafloor survey operations and this line confirmed that the positions were correct within about 2 inches with respect to one another.

OPTIONS

The key features to the Survey Spar concept are:

1. rigid (or nearly rigid) spar/mast,
2. flexible connection to the anchor,
3. simple, three channel instrumentation,
4. air ballast control, and
5. internal plumb bob calibration of overall system

There are several possibilities for extending this survey spar concept to other applications.

One obvious variation is water depth. Depending on the sea state the Survey Spar idea could be applied to water as shallow as the surfzone. The limiting factor would probably be the ability to control the spar or the tending vessel so that sightings could be made accurately. In any event the use of instrumentation to provide a first approximation to the spar base offset would certainly be an improvement over just sighting on a moored float or un-instrumented staff.

Deep water would be limited by two factors; spar rigidity and handling, and diver access. Obviously as the depth increases the pipe diameter becomes larger, the air weight goes up and so does the cost. The operation becomes more like an offshore platform construction operation than a survey. It is likely, however, that by simply floating the spar horizontally, providing corrections for spar flexure in the presence of current and towing

it to the site the present concept could probably be extended down to about 200 feet or so without major changes. Diver operations become much more complex, costly and risky in deeper water so either the spar must be limited to depths of under about 100 feet or it must be modified to provide its own mark on the bottom. Without divers to do final precise location of the anchor the installation accuracy (although not the measurement accuracy) would also be degraded.

SUMMARY

The Survey Spar system has proved to be a workable, accurate method to obtain precise survey points on the seafloor. Its accuracy is considerably better than any previously used system. The hardware is simple and the concept appears to have application to a variety of off-shore survey situations.

Accuracies of better than ± 2 inches were achieved in translating surface positions to a seafloor datum in depths to 70 feet (0.2% of water depth), under good conditions.

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REFERENCES

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