

Design of an Offshore Tripod Structure for MET/OCEAN Research

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ABSTRACT

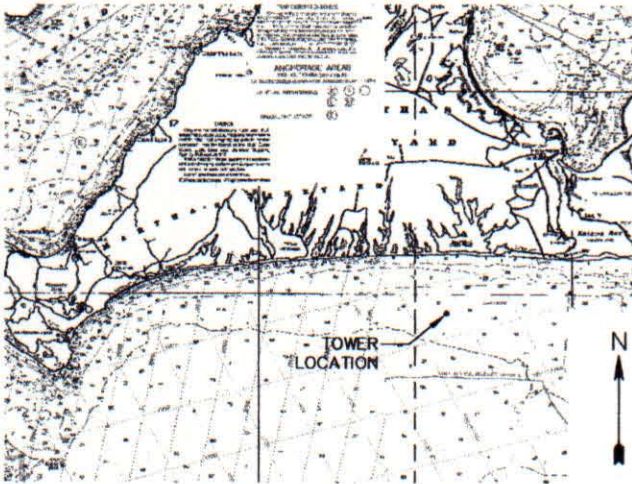
This paper describes the design and construction of a steel pipe pile tripod structure for the support of meteorological and oceanographic (MET/OCEAN) instrumentation. The structure, known as the air-sea interaction tower (ASIT), is located approximately one and one half nautical miles south of Martha's Vineyard, Massachusetts in approximately 15 meters water depth and supports a MET mast that rises to 20 plus meters above mean sea level. Design criteria included minimizing flow disturbance and vortex induced vibrations (VIV) due to the moderate to strong tidal currents. This was considered critical due to the sensitivity of the instrumentation both above and below water. Minimizing cost and rapid deployment time were also critical design considerations. The ASIT was designed for a nominal design life of 5 years that could be extended to 10 years if project funding were continued. Therefore, selection of appropriate design environmental conditions as well as corrosion protection and future dismantling issues were also given special consideration.

The utility and general design aspects of tripod structures and the analysis of slender, flexible pile structures subject to VIV are emphasized herein. Such structures may have many useful port and harbor applications such as the support of navigation aides and communications/data relay towers, guide piles/dolphins and other such isolated structures where minimal; structure, cost and construction time are of prime importance.

INTRODUCTION

The Woods Hole Oceanographic Institute (WHOI) of Woods Hole, MA has constructed a near shore offshore platform structure for the support of atmospheric and oceanographic instrumentation. The tower is named the Air-Sea Interaction Tower (ASIT) and it is part of a larger project involving the coupled boundary layer air sea transfer (CBLAST) program sponsored by the U.S. Navy Office of Naval Research and is an integral part of the WHOI Martha's Vineyard Coastal Observatory (MVCO).

This paper describes some of the unique features of the structural design and construction aspects of the air-sea interaction tower (ASIT). The ASIT is located approximately 3 kilometers south of the island of Martha's Vineyard, Massachusetts in approximately 15 m (50 foot) water depth and is fully exposed to open ocean waves from the south and southerly quadrants, see Locus Plan, Figure 1. The CBLAST program has been initially funded for five years with the possibility of future extension to ten years at which time the ASIT would be removed. WHOI requirements called for a minimal structure to support underwater instrumentation throughout the water column and a meteorological mast extending at least 10 m (33 feet) above the working platform deck level. The structure would need to produce minimum flow disturbance such as caused by proximity effects and wake interference and be free of possible vortex induced vibrations (VIV) in the prevailing tidal currents and for maximum currents of up to 1.5 m/s, approximately 3 knots. The structure would need to withstand up to 6 m (20 foot) significant wave conditions, however instrumentation would not be operational under storm wave conditions. The ASIT had to be constructed with an extremely limited budget and within a few months of the initial design



**FIGURE 1
LOCUS PLAN**

bid award. Design began in January 2002 and the ASIT was completed and operational in September 2002. WHOI provided subsurface seismic refraction survey data and seabed surface cores that indicated medium sands and sandy gravel for a considerable depth. The project schedule and budget did not allow for borings to be taken which added a feature of flexibility to be considered in design concepts. A steel pipe pile tripod was determined to be the most suitable structure type fulfilling WHOI requirements. Figure 2 is a photo of the completed structure.

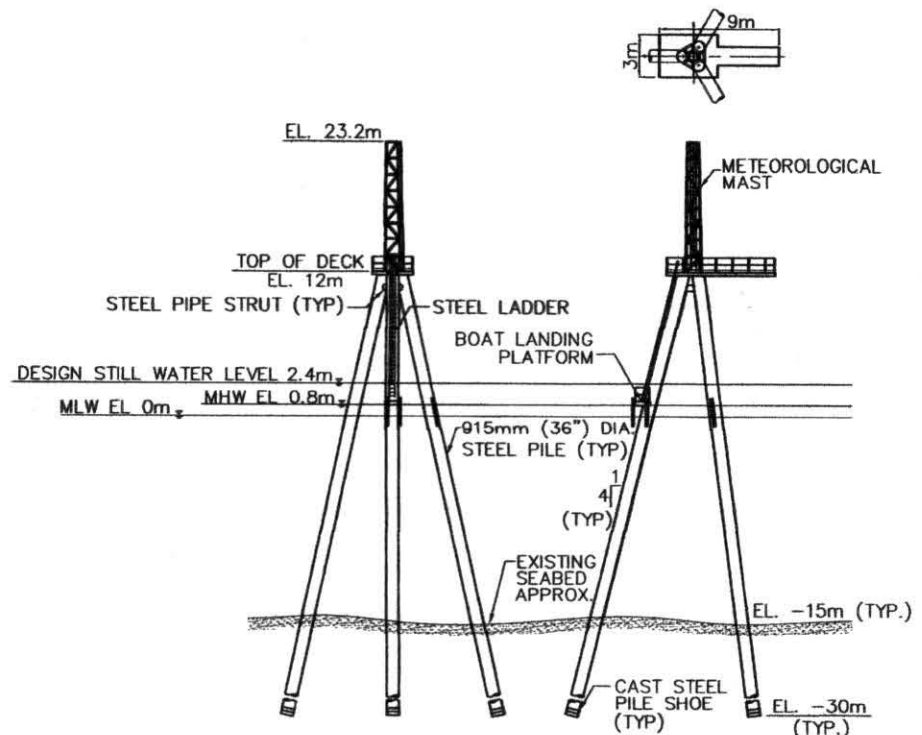
**FIGURE 2
COMPLETED ASIT**
Photograph Courtesy of Woods Hole
Oceanographic Institute



TRIPOD STRUCTURE

A symmetrical tripod structure consisting of three steel pipe piles at 120 degrees apart and interconnected only at the top was determined to be the minimum structure meeting the basic design requirements. The three piles were all battered at a slope of 1 horizontal to 4 vertical, which was determined to be a good compromise between lateral capacity and practical constructibility issues. The piles were driven open ended and were not filled with concrete or

other materials primarily for cost considerations. Figure 3 shows the general arrangement and principal dimensions of the ASIT.



Khanna & Wood (1979) described the application of groups of pile tripods to construct berthing structures in very fast river currents where vortex shedding induced oscillations would have destroyed vertical cantilevered piles during construction. Their design assumptions were validated by physical model tests carried out at the British Hydromechanics Research Association (BHRA) laboratories. Tripod structures present an efficient means of supporting relatively small and light vertical loads but moderate to high lateral loads that may come from any direction. Although the subject structure is radically symmetric with equal angles between all piles, tripods can be built unsymmetrically and with unequal pile batters such as with one vertical pile for a mooring guide pile application. A symmetrical tripod allows analysis in two basic planes that repeats every 30° for loads from any direction. The elimination of bracing reduces wave and current loads and simplifies construction although tripods can be constructed in jacket/template manner similar to offshore oil platform construction. Such applications may include foundation support for antennas, communications towers, light duty guide piles and dolphins and navigation aides etc. Elwood & Lund (2003) describe the application of a tripod structure to support a USCG lighted range marker in a busy deepwater navigation channel.

DESIGN CRITERIA

The determination of structural environmental design criteria included the selection of maximum wind, wave, current and extreme water levels appropriate to the structures nominal five-year design life and intended use. Seismic, ice and collision forces were not considered due to this short design life. The important functional performance criteria of minimal vibrations under daily and seasonal tidal currents are discussed subsequently. It was determined that designing for

a 20-year event would carry the same level of risk in terms of the probability of occurrence of design conditions occurring during the structures design life as designing for a 100-year event for a structure with a 25-year design life. WHOI had stipulated that the structure be designed to survive a 6m (20 foot) wave. A cursory examination of USACE Wave Information Study (WIS) hindcast wave height data and NOAA, NOS National Data Buoy Center (NHBC) archive data revealed this to roughly correspond to a 20-year significant wave height recurrence interval. The controlling maximum design wave height was taken to be $1.8 \times H_s$ or 11m (35 feet), with a corresponding period of 12 seconds. Available wind record data indicated a 20-year design wind speed of approximately 38 m/s (70 knots) fastest mile at 10 m height (33 feet) from any direction. Maximum currents (tidal plus wind stress), were taken to be 1.5 m/s (3 knots) with an east/west set and a storm surge water level of 1.5 m (5 feet) was added to the nearly 0.9 m (3 foot) normal high tide for the wave and current load analysis. This also resulted in the bottom of platform elevation being set at 10.7 m (35 feet) above mean low water (MLW) which allowed only a minimum air gap above the design wave crest due to cost and construction considerations. An assumed thickness of 76 mm (3 inches) of hard fouling or 152 mm (0.5 foot) increase in pile diameter was added from the mud line to mean high water (MHW) level. The ASIT also needed to be fitted with a small boat landing and working platform deck with a powered davit hoist.

VIV ANALYSIS

Fluid flowing around a relatively slender, flexible member may periodically shed vortices from alternate sides of the member resulting in both longitudinal “in-line” forces and transverse “cross-flow” forces. The period of the shedding of vortex pairs is determined by the non-dimensional Strouhal number (S_n) given by:

$$S_n = \frac{f_{vs} D}{V} \quad \text{where: } f_{vs} = \text{vortex shedding frequency}$$

$$D = \text{diameter of cylinder (or principle dimension)}$$

$$V = \text{velocity of steady flow}$$

The value of S_n varies slightly with Reynolds number but can generally be taken as about 0.2 for a circular cylindrical cross section for most engineering applications of interest herein. The following discussion pertains to cylindrical sections in particular but is also generally applicable to other shapes as well. When f_{vs} is equal or near equal to the member natural frequency (f_n) resonance may occur in cross-flow motion and when $f_n = 2f_{vs}$ resonance may occur in in-line motion. At resonance a phenomena called “lock-in” may occur where the oscillations become self excited and controlled by the structures deflections. Whether or not in-line or cross-flow motions occur is mediated by the non-dimensional reduced velocity (Vr) given by:

$$Vr = \frac{V}{f_n D}$$

Cross-flow motions are generally more severe than in-line motions and occur with values of Vr between about 3.5 and 7.5 with a peak around 5.5. The amplitude (y) of motion as given by the reduced amplitude, y/D , may approach or exceed 1.0 resulting in catastrophic motions. In-line motions are initiated at a Vr of about 1.2 and exhibit two peaks at around 1.9 known as the

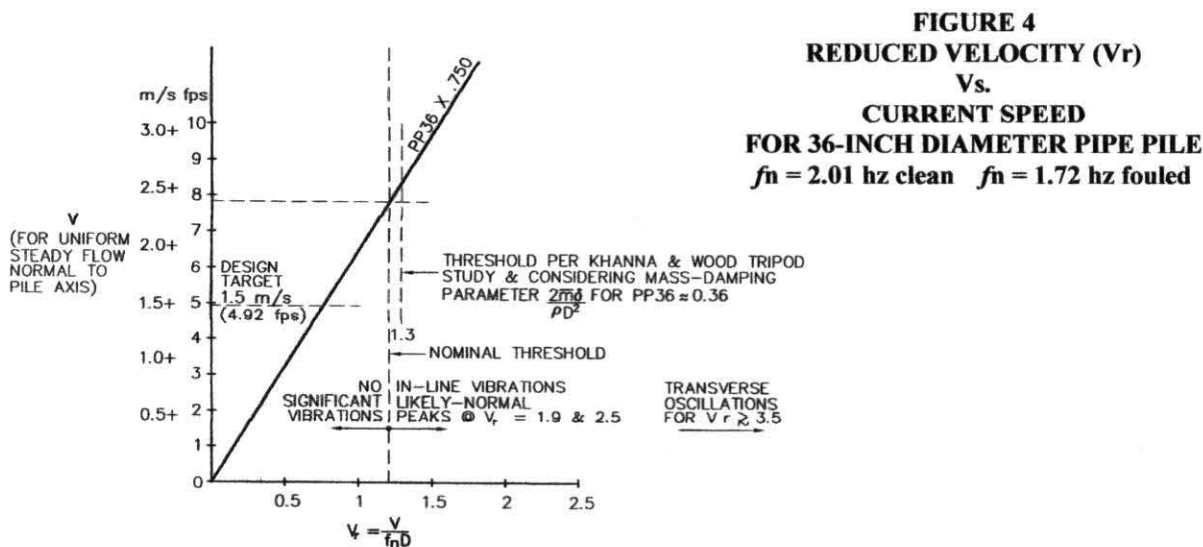
first instability region associated with the simultaneous shedding of eddies from both sides of the cylinder and a second instability region at about 2.6 associated with the shedding of a single eddy from one side. In-line motions usually peak at values of y/D less than 0.2. The amplitude of motion is moderated by the stability number (K_s) (King, 1977), which is a mass/damping parameter reflecting an energy balance at resonance and is given by:

$$K_s = \frac{2Me\delta}{\rho D^2}$$

where: Me = effective equivalent mass per unit length of pile including added mass and internal water

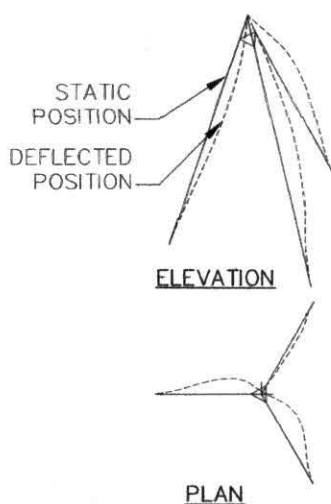
 δ = log decrement of damping ρ = mass density

In general in-line motions will be suppressed for K_s equal to and greater than 2.0 and cross-flow motions for K_s greater than about 17. As VIV motions are self-excited and increase rapidly over only a few cycles the only practical way to deal with them is to avoid them. This can be accomplished for a given flow velocity primarily by increasing pile diameter and mass/damping properties. The calculation of Me is relatively complex even for simple structures. Mechanical linkage of individual piles into arrays complicates the analysis even further due primarily to wake interference effects. However, King notes that isolated cylinder criteria can be applied for



in-line motion provided the cylinder spacing is equal to or greater than $5D$. The BHRA tripod tests described by Khanna and Wood confirmed that the tripods behaved essentially as an assemblage of individual piles. The restraint of the pile top connection and size of any capping mass, very small in this case, also effect the calculation of K_s . Design guidance was taken from Hallam et. al. (1978) and BSI (1984). Using non-dimensional graphs from Hallam et. al. and taking $\delta = 0.08$ per data provided in Hallam, a value of $K_s = 0.36$ was calculated for a 36-inch

by 0.750-inch wall pipe pile as finally designed for. This relatively low value could result in unacceptable motions unless Vr were kept comfortably below the threshold onset value of 1.2. Figure 4 shows a plot of Vr versus V for a 36-inch pipe pile that meets and exceeds the criteria. Smaller pile sizes were also investigated, the smallest meeting the VIV criteria was 32 inch D , however it was overstressed under design wave load conditions. A modal analysis using the finite element program ANSYS was conducted to determine the pile structure natural frequencies. A plot of the bowstring mode shape for the controlling lowest natural frequency is shown in Figure 5. The modal analysis was run for both the clean and fouled pile conditions and accounted for both added hydrodynamic mass and internal water up to MHW. The lowest natural



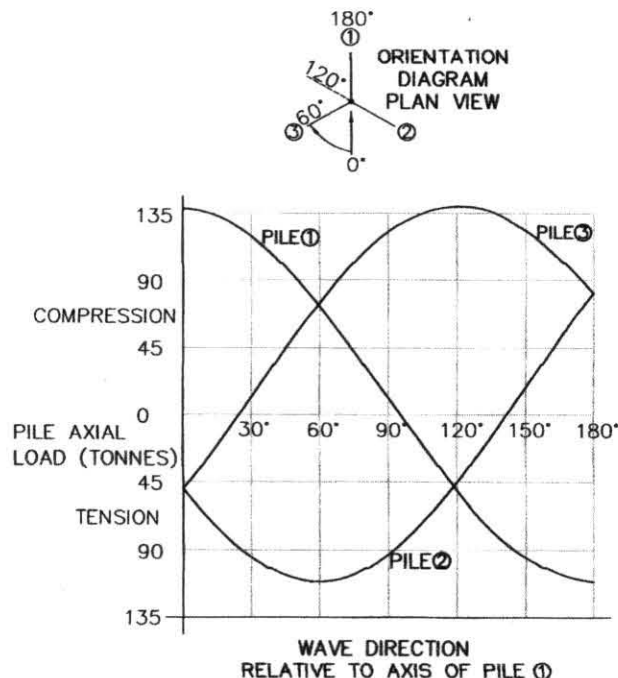
**FIGURE 5
TRIPOD MODE SHAPE FOR LOWEST
NATURAL FREQUENCY**

frequencies were found to be 2.01 hz for the clean piles and 1.72 hz for the fouled condition. Interestingly, both conditions result in nearly identical values of Vr as the increased value of D counteracts the lower value of f_n . An analysis of potential VIV under unsteady flow, waves, was not conducted considering the complexity of such analysis and the fact that instrumentation was not intended to be in use during significant wave action.

STRUCTURAL DESIGN

Key aspects of the ASIT structural design included; determination of pile loads and capacities, strength of piles to resist design wave and other environmental loads and design of the top connection. The program ANSYS was used for most of the structural analysis due in part to its extensive pipe element library. Design guidance for wave loads, pile capacities and member design was taken from API, RP-2A (1993). The structure was modeled assuming piles were fixed at a depth of fixity below the seabed determined to be 4.6 m (15 feet). Wave forces were calculated using Deans Stream Function Theory (Dean, 1974) and checked against results using the non-dimensional graphs in the USACE Shore Protection Manual (USACE, 1984).

FIGURE 6
PILE LOADS
Vs.
WAVE DIRECTION



A dynamic analysis of wave forces was not conducted considering the time and expense of such analysis and the fact that the structures lowest natural frequency corresponds to a period of only about 0.6 seconds, well below the range of any significant wave forces. The design wave force was dominated by the drag force component at the wave crest position. Preliminary calculations revealed that only a small force reduction could be taken in the total force and therefore the total force was taken as the sum of the maximum individual pile load acting simultaneously on all three piles. The total wave force was 84 tonnes (186 kips) acting at just below the design still water level, elevation +2.4 m (+8 feet) MLW. Sustained wind acting on the MET mast and superstructure brought the total design lateral force to 86 tonnes (190 kips). Resulting pile loads versus wave direction based on the ANSYS analysis are shown in Figure 6. Buoyant uplift was added at the waves crest position to derive the design tension capacity of 254 kips. A minimum factor of safety of 1.5 was specified for the maximum design wave condition. Specified design load capacities were 232 tons compression and 190 tons tension. Pile tension capacity was seen as the most critical requirement and therefore field monitoring was called for as described following.

The top connection was another critical design feature. Pile end forces and moments induce wracking and torsional stresses in the connecting structure. The top connection consisted of a one inch thick capping plate and horizontal pipe struts with web plates between piles, struts and cap plate. Continuous full penetration groove type welds were used on all interconnected parts to address fatigue concerns. A one eighth inch corrosion allowance was added to the pile wall thickness to address underwater corrosion and the superstructure and piles above MHW were given a three coat urethane protective coating.

CONSTRUCTION

The design of the ASIT structure was kept simple to allow construction by regional marine contractors, in addition to producing an aerodynamically/ hydrodynamically clean structure. Jack-up barges able to work offshore in 15m (50 foot) water depths were not regionally available, so the design was based on constructing the tripod tower with individually driven pipe piles in a similar manner to typical port and harbor dolphin construction.

The ASIT construction was competitively bid with an aggressive construction schedule. The contractor prefabricated each of the 49 m (160 foot) pipe piles, superstructure and meteorological mast in port and then transported these elements to the site on an ocean service deck barge. The barge was moored at the site at the beginning of August 2002, using multiple seabed anchors and a three pile braced false work structure was installed at the correct location. The false work included alignment guides for the battered tower piles, and each tower pile was installed open ended to just above the specified tip elevation using a vibratory hammer, and then driven to capacity using a single acting diesel impact hammer.

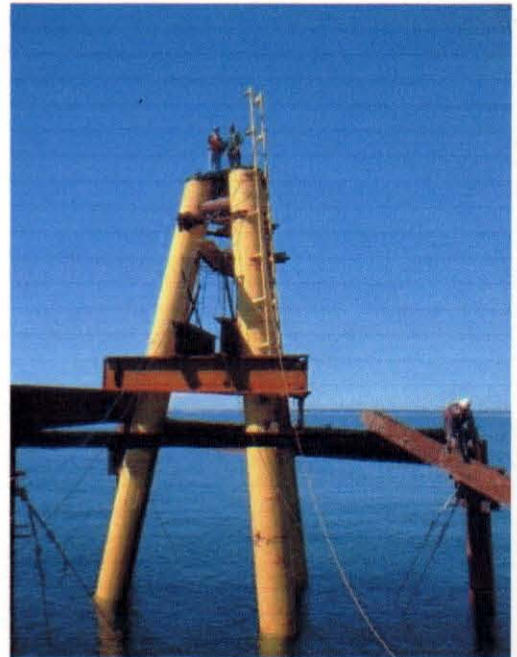
The first tower pile installed was monitored with a dynamic pile driving analyzer (PDA) to allow determination of both compressive and tension capacities, and to establish the pile acceptance criteria of the following two piles. The dynamic analysis indicated that this friction pile developed approximately 80% of its compressive capacity from skin friction. The actual pile compressive capacity was estimated to be 220% of the minimum required ultimate compression capacity of 210 tonnes (232 tons), while the actual uplift capacity exceeded the minimum required ultimate tension capacity of 172 tonnes (190 tons) by 140% to 180%.

Once all three tripod tower piles were installed, the pile heads were connected, the prefabricated deck, met mast, boat landing and ladders were installed, and the false work was removed (see Figure 7). The ASIT was substantially complete by mid September 2002, which did include some weather delays and barge demobilization in early September to avoid hurricane *Gustav*. Following construction of the tower, scientists from WHOI installed a seabed fiberoptic data cable to shore and outfitted the tower with instrumentation to measure air-sea interactions, ocean mixing, gas exchange, bio-optics and sediment transport.

CONCLUSION

The tripod structure described herein has met the owners needs for a aerodynamically/ hydrodynamically clean structure, relatively low cost and short design and construction schedule, as well as providing a suitable work/support platform with minimal flow disturbance and response to potential VIV. The simple tripod design is well suited to construction of near shore, port and harbor towers and dolphins, with readily available marine construction equipment.

FIGURE 7
CONSTRUCTION OF ASIT
Photograph Courtesy of Woods Hole
Oceanographic Institution



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