Experimental Estimation of Material and Support Properties for Flexible Dolphin Structures

Pokusna procjena svojstava materijala i nosača za fleksibilne privezne stupove

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Summary

Present work describes the inverse problem for identification of material and support type properties of flexible dolphin structure. Most liquid bulk terminals are equipped with a jetty as berthing facility. The ship mostly berths to dedicated breasting dolphin structures, which can be single-pile flexible/rigid dolphins or multi-pile flexible/rigid dolphins. This work considers dolphin motion as mass-spring damped system where cantilever approximation mimics dolphin pile. Few measurements have been made for the dolphin structure, which is approximately 30 m long, 15 m immersed in the bottom and placed about 2-3 m above the sea level. The elastic material properties and pile support were identified via inverse method combined with displacement measurements of dolphin head.

KEY WORDS
cantilever beam
flexible dolphin pile
material properties
support type

Sažetak

U radu se opisuje inverzni problem identifikacije svojstava materijala i tipa nosača za fleksibilni privezni stup. Gatovi se koriste za privezivanje pri većini terminala za tekući teret. Brod se većinom vezuje za predviđene stupove za pristajanje koji se mogu sastojati od jednog ili više stupića i mogu biti fleksibilni ili kruti. U radu se razmatra kretanje priveznog stupa poput sustava masa – opruga – prigušnik, pri čemu aproksimacija konzolnog nosača oponaša privezni stup. Malo je mjerenja strukture priveznog stupa; dužina je otprilike 30 metara, 15 metara uronjeno je u dno, a 2 – 3 metra iznad je morske razine. Elastična svojstva materijala i nosač stupa identificirani su inverznom metodom u kombinaciji s mjerama istisnine glave priveznog stupa.

KLJUČNE RIJEČI
konzolni nosač
fleksibilni privezni stup
svojstva materijala
tip nosača

1. INTRODUCTION / *Uvod*

The contemporary increase of ship dimensions and capacity require reengineering of some current harbour facilities. Among them are e.g. mooring and breasting flexible pile dolphins[1]. Their lifetimes heavily depends on the material used in the construction and proper usage. The directions on dolphin design are given in Schmid report [2], Tomlinson and Woodward book [3], and British standard [4]. Detailed studies of dolphin structures and their interactions with support can be found in the additional literature. For example in the work of Zhang with co-authors [5,6] and Xu with co-authors [7] they study complex nonlinear effects of laterally loaded rigid piles in cohesive soil. Fan and Yuan [8] use high-resolution finite element models of the ship– structure–soil interactions to analyse the plasticity effects on the flexible dolphin structure and its support. Farag with co-authors [9,10] propose an advanced reliability evaluation procedure for analysis and design of mooring dolphin with the use of hybrid response surface and second-order reliability method approach.

In this paper an inverse procedure to estimate the stiffness and support of dolphin structure based on the beam theory will be presented. Simplified models are derived from the beam theory [11] identifying the material and support properties of a flexible dolphin. Identification of the material properties and mounting support of flexible pile has been done by using the inverse procedure, which was calibrated with measurements data. The main goal is to formulate a simple procedure that will enable the estimation of operating capabilities of the existing structure in a fast and reliable way before a new design, research or a possible redesign of dolphin structure. The very similar approach was developed in [12] where they established a continuous monitoring and instant data acquisition. In our work an advanced model is proposed based on the beam theory [11].

2. MODEL / *Model*

In the British Standard [4] (and many other standards) the maximum berthing energy is calculated with the kinetic energy approach, based on the work by Saurin [13]. The basic assumption in the kinetic energy approach is that the kinetic energy of the ship at the moment of the first contact with the berthing structure is to be absorbed by the berthing structure (fender and structure itself). The influence of the motions of the ship (the ship's position relative to the berthing structure and the surrounding water) on the loads acting on the berthing structure results in additional factors to be applied in the design of the structures. The dolphin should absorb all the energy of impact by lateral deflection of the piles [4]. The pile

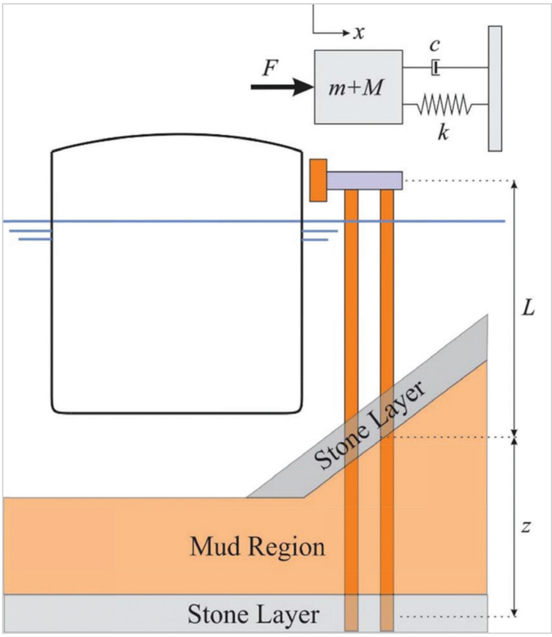

Figure 1 Situation of dolphin structure in the investigated problem. Above is a scheme of mass spring damped system as the approximation model for the structure dynamics

Slika 1. Stanje strukture priveznog stupa u istraženom problemu. Iznad je shema sustava masa – struna – prigušnik kao aproksimacija modela dinamike strukture

should operate so that the absorption energy is a function of the square of the bending stress. The pile section should be selected to operate at 0.8 yield stress under abnormal energy conditions. For the recommended ratio between abnormal and normal energies of 2.0, this gives the normal energy bending stress as 0.57 yield stress.

The main assumption on the ship-dolphin impact interaction uses simple mass-spring damped model (Figure 1) of the impact of a mass with spring. At impact, by the conservation of linear momentum and total inelastic impact, the initial speed of the dolphin head after an impact (v_0) reads

$$v_0 = \frac{M}{m+M}V_0 \tag{1}$$

where V_0 is the ship approaching speed, *M* is the ship mass and *m* is the dolphin mass. Motion after impact is governed by the energy conservation. In particular the maximal dolphin deformation Δ (Figure 2) can be obtained from the balance of kinetic energy and the elastic energy

$$\frac{1}{2}(m+M)\,v_0^2 = \frac{1}{2}k\,\Delta^2 \tag{2}$$

where *k* is stiffness coefficient of dolphin structure. From the Eq. (2) the maximal deflection is

$$\Delta = v_0\sqrt{\frac{m+M}{M}k} = V_0\sqrt{\frac{M}{k\left(1+{}^{m}\!/_{M}\right)}} \tag{3}$$

Always is the case $m \ll M$ and from Eq. (3) it follows

$$\Delta \approx V_0\sqrt{\frac{M}{k}} \tag{4}$$

where are now V_0 and M design parameters. If *k* is known Δ can be calculated, but in our case the task is inverse and Δ is known and *k* can be estimated by

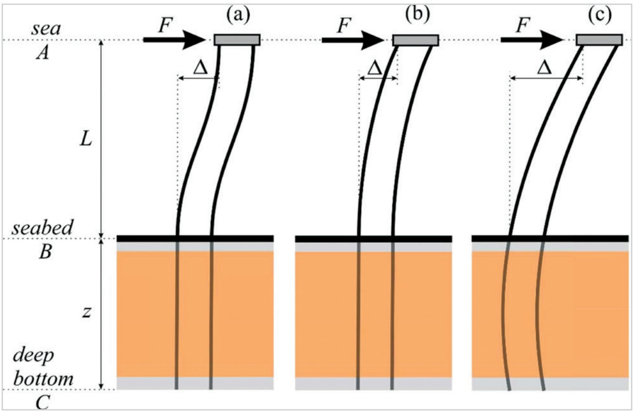

Figure 2 Three different type of cantilever supports: (a) - clamped at *A* and *B*; (b) - clamped at point *B* simply supported at *A*; (c) - doubly simply supported

Slika 2. Tri tipa konzolnih nosača: (a) – stegnuti na A i B; (b) – stegnuti na točki B jednostavno oslonjen na A; (c) – dvostruko jednostavno oslonjen

$$k \approx M\frac{V_0^2}{\Delta^2} \tag{5}$$

Let us assume that the cantilever models the flexible dolphin structure and its deflection is

$$x = \Delta = \frac{F\,L^3}{\kappa\;\alpha} \tag{6}$$

where $\kappa = E\,I$ is cantilever bending stiffness (E-elastic modulus, I-beam cross section moment of inertia), F is the force applied at the end of a cantilever, L is its length and α is a parameter that depends on a type of dolphin mount on the seabed. In this problem, three typical situations (Figure 1) are considered for the parameter α. If fender on the top of the pile is clamped (Figure 1-a) then parameter $\alpha = 12$, else if support on top is simple (Figure 1-b) then parameter $\alpha = 3$ and if double simple support is assumed (Figure 1-c) then parameter $\alpha = \frac{3}{1+{}^{z}\!/_{L}}$.

When it is assumed that the deformation is small then only linear isotropic elasticity effect is present. By the linear elastic theory the relation between the force and the deformation is

$$F = k\,x = k\,\Delta\,, \tag{7}$$

and the Eq. (6) can be rewritten in a form

$$k = \alpha\frac{\kappa}{L^3} \tag{8}$$

defining the dolphin structure stiffness. From Eq. (8) it can be seen that the dolphin structure stiffness constant depends on the three variables

$$k = k(\alpha,\kappa,L) \tag{9}$$

Since in our test only *k* is indirectly measured we can from Eq. (8) calculate only one parameter. Since κ and *L* are at least approximately known we can estimate i.e. approximate type of dolphin mounting. To justify this approach let us look at the sensitivity of the dolphin structure stiffness. From Eq. (8) and (9) we derive the total differential for stiffness coefficient of dolphin structure

$$dk = \frac{\partial k}{\partial\alpha}d\alpha + \frac{\partial k}{\partial\kappa}d\kappa + \frac{\partial k}{\partial L}dL = \frac{\kappa}{L^3}d\alpha + \frac{\alpha}{L^3}d\kappa - 3\alpha\frac{\kappa}{L^4}dL \tag{10}$$

and it immediately follows

$$\frac{dk}{k} = \frac{d\alpha}{\alpha} + \frac{d\kappa}{\kappa} - 3\frac{dL}{L} \tag{11}$$

In Table 1 the estimated values of each term in Eq. (11) from our study problem show the relation of similar order on the structural stiffness *k*. For our problem it was observed that the support coefficient α is an order of magnitude bigger than the other two parameters (κ, L). The support coefficient α has the most relevant influence on dolphin structural stiffness.

Table 1 Estimate of values for terms in Eq. (11)
Tablica 1. Procjena vrijednosti za jednadžbu (11)

Term	Mid Value	Error	$\frac{d\bullet}{\bullet}$
k	$5 \cdot 10^5$ N/m	$2.5 \cdot 10^5$ N/m	10^0
α	8	9	10^0
κ	10^9 Nm^2	$2 \cdot 10^8$ Nm^2	10^{-1}
L	18 m	2 m	10^{-1}

In Table 2 the relations for the maximal dolphin head deflection Δ and the dolphin structure bending energy *U* are derived. If it is supposed that the kinetic energy is completely transformed into the bending energy than we can find the bending stiffness coefficient κ with the help of formulas in Table 2. Bending energy also depends on the number of piles in dolphin structure and the kinetic energy is redistributed to each pile.

Table 2 Expressions for maximal deflection Δ and deflection energy U with respect to pile support configuration (Figure 2) for linear elasticity model (Beam theory [11])
Tablica 2 Izrazi za maksimalni otklon Δ i energiju otklona U u odnosu na konfiguraciju potpornih stupića (Slika 2) za model linearne elastičnosti (Teorija grede [11])

	Figure 2-a	Figure 2-b	Figure 2-c
maximal deflection Δ	$\frac{F L^3}{\kappa}\frac{1}{12}$	$\frac{F L^3}{\kappa}\frac{1}{3}$	$\frac{F L^3}{\kappa}\frac{L+z}{3L}$
deflection energy *U*	$\frac{F^2 L^3}{\kappa}\frac{1}{24}$	$\frac{F^2 L^3}{\kappa}\frac{1}{6}$	$\frac{F^2 L^3}{\kappa}\frac{z^2}{6L^2}$

3. MEASUREMENTS AND DATA PROCESSING / *Mjerenja i obrada podataka*

Laser speedometer was used in the conducted measurements of the dolphin head displacement. At Figure 3 (blue line) the typical displacement distribution shows the damping oscillations of the dolphin head. When the ship touches the structure ($t = 0$ at Figure 3) the impact occurs. The dolphin starts to oscillate in a dumped mode. Data where fitted to the nonlinear model of the dumped oscillator

$$x = x_0 + A\sin\left(\omega_0 t + \delta\right)e^{\gamma t} \qquad (12)$$

where

parameter	unit	description
x_0	m	equilibrium position
A	m	initial amplitude
γ	$1/s$	damping coefficient
ω_0	$1/s$	natural frequency
δ		shift in phase

In fitting procedure, only data in the yellow region (Figure 3) were used. Fitting model reveals that the oscillations are slowly damped (under damped mode) and the damped frequency of structure

$$\omega_d = \omega_0\sqrt{1-\zeta^2},\ \zeta = \frac{\gamma}{\omega_0} \qquad (13)$$

is already $\omega_0 = 0.1288\,s^{-1}$. The effect of damping can be neglected in the frequency calculations. Using natural frequency of the structure and mass of the system, dolphin structural stiffness can be immediately calculated

$$k = \omega_0^2\left(m+M\right) \approx 597.3\text{kN/m} \qquad (14)$$

Knowing dolphin structural stiffness the estimate of the parameter of support type reads

$$\alpha = \frac{k L^3}{\kappa} \approx 1.74$$

where bending stiffness was set to $\kappa = E I = 2\cdot 10^{11}\,\text{N/m}^2\ 10^{-2}\,\text{m}^4 = 2\cdot 10^9\,\text{N/m}^2$ and $L = 18\,\text{m}$. It is highly possible that the dolphin structure is double simple supported (Figure 2-c).

In Eq. (8) it was assumed that the relation between the force and deformation is linear. Let us analyse the situation if the relation is of non-linear type

$$F = k\,x^\lambda \qquad (15)$$

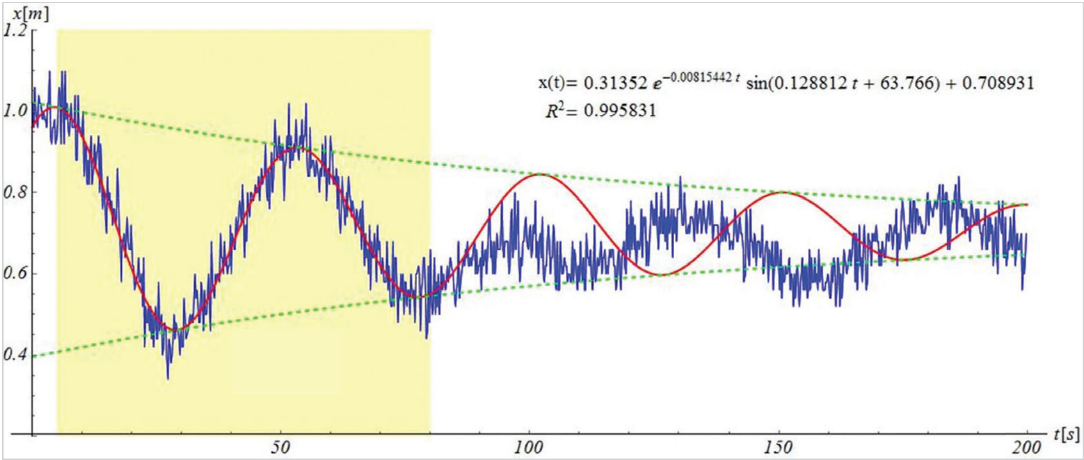

Figure 3 Plot of measured data (blue line), fitted model (Eq. – red line) where coefficient of determination $R^2 = 0.99$ was determined only for data in yellow region, dotted green lines show damping boundaries.
Slika 3. Ucrtavanje izmjerenih podataka (plava crta), postavljeni model (Eq. – crvena crta) gdje je koeficijent determinacije $R^2 = 0.99$ određen samo za podatke u žutom području, točkaste zelene crte pokazuju granice istovara

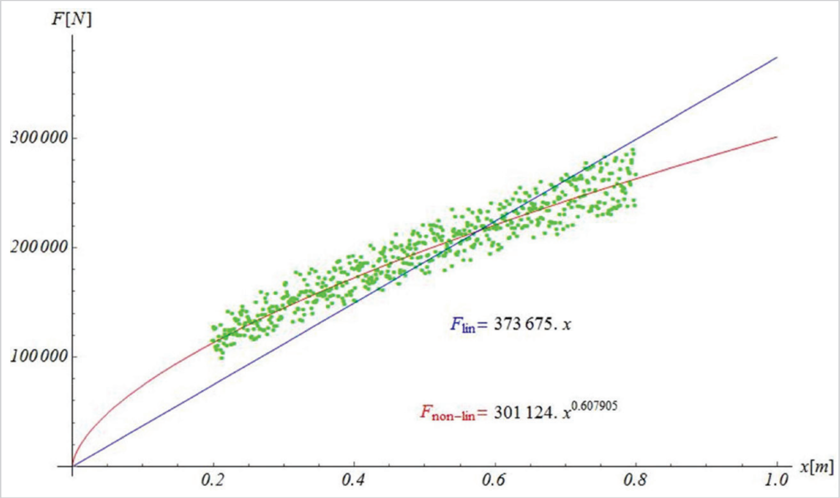

Figure 4 Monte-Carlo experiment modelling pile structural response data (green). Data are fitted with two models linear (blue) and non-linear (red)

Slika 4. Monte-Carlo eksperiment, podaci strukturnog odgovora modela stupića (zeleno). Podaci imaju dva modela, linearni (plavi) i nelinearni (crveni)

Using Eq. (6) and (15) we derive the nonlinear relation for dolphin structure stiffness

$$k = k(x,\alpha,\kappa,L) = x^{1-\lambda}\,\frac{\kappa\,\alpha}{L^3} \tag{16}$$

Now, to determine the structural stiffness additional information of the maximal pile deflection must be provided with the knowledge of the nonlinear structural coefficient λ. Minimal three measurements are needed to calculate coefficient λ. For example, in nonlinear model structural stiffness is always smaller and pile maximal deflection will be larger compared to the linear stiffness model. In Figure 4 the simple Monte-Carlo experiment shows the difference in the linear and nonlinear model approach. The model difference can lead to the predication error of 10%-20%.

4. DISCUSSION AND CONCLUSIONS / *Rasprava i zaključci*

The proposed methodology can be a first step in the material support type examination of flexible dolphin structures. For example in the work of Metzger, Hutchinson, and Kwiatkowski [13] they have analysed the similar situation. In a similar fashion with continuous data assembly, it is possible to estimate, with a high confidence, different properties of flexible dolphin structures in a very simple, fast and non-invasive way. There was exposed a single experimental case showing the procedure with elementary calculations. Based on many experiments the model can be modified to the nonlinear response function $F = k\,x^{\lambda}$ (Figure 4), where it can be expected $\lambda < 1$, resulting in a softer dolphin structure material. Nonlinear material response represents a real life situation and cannot be simplified. The combination of simple models discussed in this work and e.g. in [13] joint in a single toolbox can be a practical tool in the cheap and fast estimation of different parameters of flexible dolphin structures.

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