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Biodynamic timber sheet pile – vegetation retaining structure

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Abstract

Timber sheet pile walls are widely used for the protection of stream banks in different parts of the world. However, there is tendency of creating more sustainable types of stream banks not only because exploitable wood is more difficult to obtain, but also because of disturbance to the natural habitat of plants and animals due to hard embankments. In The Netherlands alone, about 2500 km of engineered timber sheet pile wall embankments exist, primarily made with tropical hardwood, apart from an even much larger amount of ′non-engineered′ small size timber based embankments. As an alternative, the authors propose to use a mixed timber sheet pile-vegetation system, where locally available timber can be applied in combination with natural vegetation. Unlike the usual bioengineering scheme, vegetation is not seen as an element, which could replace the timber sheet piles. Instead a new perspective is tested, where the vegetation is included as a ′structural′ element which will reduce or even counteract the consequences time dependent biological degradation of the timber sheet pile. By doing so, both long term durability as well as reliability of the stream bank are improved. We have developed a comprehensive design model, based on well-established sub- models from the literature on plant growth as well as timber service life. The timber sheet pile wall-vegetation system is illustrated in an example case study. Preliminary analysis including only the mechanical reinforcement of vegetation shows that the durability of timber sheet piles is enhanced. Thus, using vegetation in combination with highly degradable timber could possibly negate the need for using hardwood timber, or more generally, save resources that are currently used for these structures.

1. Introduction

A study of the evolution of bioengineering techniques by (Evette et al., 2009) shows evidence of the use of woody species to stabilize river banks dating back from 16th century. Prominent examples include that of King Frederick William 1 of Prussia who ordered to plant willow on river banks and that of Dugied in France, who suggested to plant exotic species like Chinese Varnish Tree (Toxicodum_verricifluum (Stokes) F. Barkley) and White Mulbery (Morus_alba L.) to form dense barriers (Evette et al., 2009; Dugied, 1819). Ecological engineering techniques have being well recognized and implemented in many riverbank restoration and protection projects (Li et al., 2006; Anstead and Boar, 2010; Anstead et al., 2012; Evette et al., 2009). The first and second principles of ecological engineering as stated by (Bergen et al., 2001) requires that the designs produced mimic natural structures and are site specific. The concepts of energy efficiency, independence of design and functional requirements are addressed in the third and fourth principle.

Ecological bioengineering involves the use of live plants in combination with inert material to protect and conserve soil. The plant roots are expected to provide mechanical reinforcement to the soil while the evapo-transpiration provides hydrological reinforcement. Mickovski and Tardío (2016) used live plants in combination with wood to develop a dynamic soil bioengineering scheme, which was validated on a slope stabilized by crib wall and willow. Ollauri and Mickovski (2014) developed an integrated model taking into account the hydrological and mechanical effects of vegetation that could be used with easy input parameters. Different types of bioengineered structures were analysed by Fernandes and Guiomar (2016) some 20 years after construction. The effect of riparian vegetation in stabilizing streambanks was studied and quantified in the pioneering works of Thomas and Pollen-Bankhead (2010), Simon and Collison (2002), Pollen-Bankhead and Simon (2009) etc.

Riverbank degradation has societal and environmental impacts. Timber sheet piles are often used as stream bank protection structure. Timber sheet piles are considered environmental friendly compared to other conventional solutions like concrete walls or steel sheet piles. Sometimes, tropical hardwoods which have better resistance to decay may not be locally available, and have to be imported. For example, The Netherlands has about 2400 km of engineered timber sheet pile, while it has very less exploitable tropical hardwoods (Van de Kuilen and Linden, 1999). Thus, there is a need for an alternative solution, which involves locally available material and at the same time fits into the scope of ecological engineering. A timber sheet pile –vegetation composite stream bank protection structure is proposed in this paper an alternative to currently employed conventional methods. The mechanical reinforcement of the soil with growth of vegetation could result in a reduction of bending moments and shear stresses acting on the sheet pile over time, thereby decreasing the duration of load effect in the timber and counteracting the effects of slow biological degradation of wood in air-water-soil conditions. Researchers have pointed out the need for including dynamic nature of vegetation roots in slope stability analysis, Stokes et al., (2009). To the best knowledge of the authors, there exist no study focusing on a bio- engineered stream bank retaining structure, which takes into account the specific characteristics of the riparian vegetation root growth, dynamic nature of the roots, variation in moment and shear acting on the sheet pile and the reduction of time dependent damage in the sheet pile. The basic methodology adopted in any bio-engineered structure is the design of stress transfer between the inert material and the vegetation. This eventually leads to the vegetation supporting the slope and the inert material decaying away. The authors would like to see the effect of vegetation from a different perspective. As mentioned earlier, one of the key issues faced in countries like the The Netherlands is the non-availability of high decay resistance hardwood. Thus, in this study vegetation reinforcement is hypothesised as an element which reduces the damage accumulated on the low decay resistance sheet pile, thus providing a valuable alternative.

2. Materials and methods

2.1 Model components

We attempt to understand the development of a timber sheet pile-vegetation system and characterize the effect of vegetation on the time dependent load carrying capacity of vegetation - timber sheet pile system. After introducing the components of the model, first, a conventional sheet pile without anchor is evaluated (Case 1), see Fig 1. Second, the timber sheet pile –vegetation system is analysed in a time framework with growth of vegetation and damage accumulation on the sheet pile (Case 2).

A root distribution model suitable for riparian ecosystems is employed in the model. Knowing the root distribution at each time period Δt_i, the root cohesion is estimated for that time period. Any change in cohesion of the backfill would reflect as a change in lateral earth pressure and hence as a change in bending moment and shear forces acting on a sheet pile. The variation in bending moment and shear stresses experienced by the timber sheet pile are the key parameters in the evaluation of the effect of vegetation on the sheet pile. Any change in moment would in turn result in a change in the required thickness of the sheet pile structure. Thus, the required thickness of sheet pile would become a time dependent parameter. On the other hand, the sheet pile is subjected to biological degradation and effects of load duration, especially when locally available less durable softwoods are used. This would result in a reduction of thickness of the sheet pile and hence the moment carrying capacity and shear resistance. All the component models are described briefly in the next section. The behaviour and evolution of the timber sheet pile-vegetation system is illustrated through an example application.

2.2 Root growth model

The models for root distribution proposed by Laio et al., (2006), Preti et al., (2010), Schenk (2008) are mainly intended to use in situations where the vegetation uptake relies on water infiltrating into soil (Tron et al., 2015). In riparian regions, ground water is the main source of nutrients and water for vegetation (Zeng et al., 2006), unlike in other situations where the nutrient availability decreases with depth. The roots can concentrate in top regions due to lack of oxygen resulting from high water table or can grow deep to reach the water table to exploit necessary nutrients and water. To model the effects of riparian vegetation on soil reinforcement, it is required to adopt a root distribution model, which takes into account the above mentioned situations. Tron et al., (2014) developed a stochastic analytical model for finding the vertical root distribution in ecosystems where rainfall infiltration is not the main source of plant water uptake, see equations 1 to 4:

Subsequently the CLHS is formed by butt jointing the two matched and planed half-sections. For the production of longer CLHS, as demanded for the use in reinforced soil walls (LN = 0.6 ~ 1.0 HS), a prototype press was developed. The prototype press (**Error! Reference source not found.**) is designed in C-shape for a manual loading from the front side. The main frame consists of four 160 mm thick C-shaped cross laminated timber (CLT) elements with an upper and lower pressure bar (HEB 160-S 235) placed in the recess of the CLT elements.

$$\bar{r}(z) = \frac{2\theta(z)k(z)}{\theta(z) + \theta(z)K(z) + 1 - k(z)} \quad (1)$$

$$\theta(z) = \frac{\beta(z)}{\gamma} \quad (1)$$

$$k(z) = \begin{cases} \dfrac{\Gamma\left(\frac{\lambda}{\eta}, \frac{h_1 - z - L}{\alpha}\right) - \Gamma\left(\frac{\lambda}{\eta}, \frac{h_1 - z}{\alpha}\right)}{\Gamma\left(\frac{\lambda}{\eta}\right)}, & \text{if} -\infty < z < h_1 - L \\ 1 - \dfrac{\Gamma\left(\frac{\lambda}{\eta}, \frac{h_1 - z}{\alpha}\right)}{\Gamma\left(\frac{\lambda}{\eta}\right)} & \text{if } h_1 - L < z < h_1 \end{cases} \quad (3)$$

$$\alpha = \frac{\breve{\alpha}}{h_2} \quad (4)$$

$\bar{r}(z)$ is the quantity of roots one expects to find at depth z,
$k(z)$ is the probability that a depth z falls in the optimal root growth zone,
L is the width of root box,
$\theta(z)$ is the ratio of growth rate of roots,
$\beta(z)$ to decay rate of roots γ,
λ is the mean rate of stochastic instantaneous rise of water level,
$\breve{\alpha}$ is the mean depth of the pulses,
h_2 is the depth of water table at driest periods,
η is the water level decrease in time,
h_1 is depth of the root box.

According to this model, the roots concentrate on the upper layers if the variability of the water table is high and deeper roots are found when the variability of water table is less.

2.3 ROOT COHESION MODEL

The most widely used Wu & Waldron model developed by Wu (1976) assumes that all roots grow perpendicular to shear surface and they all break simultaneously. With the availability of root distribution and tensile strength, this model can be easily implemented and is applied here. Even though this model results in overestimation (Pollen and Simon, 2005; Thomas and Pollen-Bankhead, 2010) of the assessed additional cohesion, successful application and observation has been reported (Mickovski et al., 2008; Ollauri et al., 2014). Parameters k' and k" are used to correct the overestimation. k" is the ratio between "W&W" model and the fiber bundle model developed and Pollen and Simon (2005).

$$C_r(z) = k' * k'' * RAR(z) * T_r \quad (5)$$

$C_r(z)$ is the additional cohesion due to vegetation,
$RAR(z)$ is the root are ratio,
T_r is the average tensile strength of the root.

2.4 SHEET PILE MODEL

D-Sheet piling (Visschedijk and Trompille, 2011) is a tool with graphical interactive interface used to design sheet pile walls and horizontally loaded piles. The sheet pile is modelled as an elasto-plastic beam and uniform or variable stiffness could be defined along the beam axis. Initial horizontal stress is estimated using Jáky's equation and additional stresses using Boussinesq's stress distribution theory. Soil stiffness is modelled as a series of discrete, independently acting multi linear springs, forming an elastic foundation for a beam. Options to optimize length are also included in the standard module. The elastic stiffness and an estimated depth of the sheet pile are given as input parameter's for the sheet pile. Cohesion, internal friction angle, density are given as input parameters for the soil. It is possible to define different soil layers with different properties.

2.5 TIMBER SERVICE LIFE MODEL

Timber service life modelling is generally conducted for time dependent structural safety evaluation. The prediction of rate of decay of wooden members and hence their structural strength is key to any bioengineered structure. For an ideal bioengineered structure, herein timber sheet pile-vegetation combination, the load transfer and load sharing design depends on the ability to accurately predict the contribution of sheet pile to the system with time. Effects due to variation in load and resistance determine the time dependent behaviour of the sheet piles. Timber service life models are also referred to as damage accumulation models and a number of approaches can be found in literature (Van der Put, 1986, Foschi and Yao, 1986, Gerhards and Link, 1987). These models assume that cross sections do not change over time, for instance by assuming that over time the wood material properties are not influenced by decay and the cross section is constant. A modification of exponential damage model of Gerhards (1987), for changing material properties and cross sections can be found in Van de Kuilen (2007) and Van de Kuilen and Gard (2012) for deteriorating timber piles and cracked timber beams respectively. To include the time dependent reduction in load carrying capacity of the timber when physical and biological deterioration takes place, as given in equation (6).

$$\frac{d\alpha}{dt} = \exp\left[-a + \frac{b\sigma(t)}{f_s(t)}\right] \tag{6}$$

Where $\frac{d\alpha}{dt}$ is rate of damage and α can take value of 0 to 1, 0 representing no damage and 1 representing structural failure, $\sigma(t)$ represents the history of load variation (N or Nmm), $f_s(t)$ represents the variation in load carrying capacity with time (N or Nmm). Often, instead of plotting the development of α, 1-α is plotted, indicating the residual load carrying capacity. The moment carrying capacity varies with time due to reduction of cross section, but also because the strength of the outer layers may be reduced because of biological decay. Thus, the total rate of change of the effective sectional moment of area W_I and change in effective cross sectional area $\in_A$ resisting shear can be written as:

$$\in_I = \left(1 - \frac{2\delta}{b}\right)\left(1 - \frac{2\delta}{t}\right)^2 \tag{7}$$

$$\in_A = \left(1 - \frac{2\delta}{b}\right)\left(1 - \frac{2\delta}{h}\right) \tag{8}$$

Where δ is the rate of decay per year, b is the width and h is the thickness of the sheet pile.

Thus, time dependent area and moment of area could be written as:

$$W_t = W_0 \in_I \tag{9}$$

$$A_t = A_0 \in_A \tag{10}$$

The time dependent sectional moment of inertia, area resisting shear, moment carrying capacity and shear resistance can be evaluated from the above equation while the bending moment and shear acting on the sheet pile could be obtained from the D-sheet piling software.

2.6 Case study

To illustrate the model and understand the effect of vegetation on the damage induced on the sheet pile a case study at the stream bank location in Huairuou District, Beijing China is chosen. This location is ideal for the case study, due to readily available biomass measurements of Salix alba L. for 5 and 7 years from the experimental study by Zhang et al., (2018). The detailed soil description is also available for the location. A 3 meter high stream bank made of sandy loam and loamy sand is to be retained. The internal friction angle of the soil is chosen to be 30^0 with no cohesion. The density of the embankment is taken as $18kN/m^3$. A timber sheet pile retaining structure (Case 1) is compared with a timber sheet pile-vegetation structure (Case 2) for a design life of 20 years, see Fig 1.

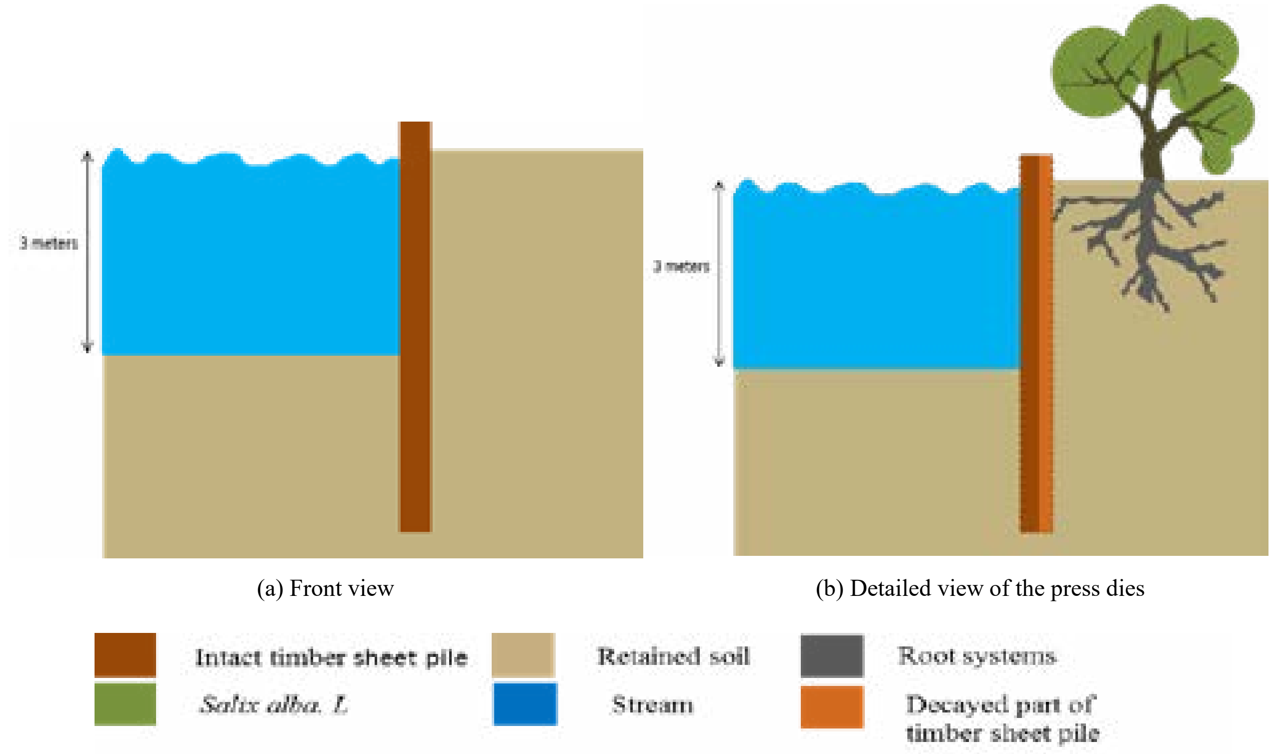
3. Results & Discussions

3.1 Root distribution model

For any location the root distribution model given by Tron et al., (2015) needs to be calibrated for prediction of the root distribution with depth. The temporal variation of Salix alba L. 'Tristis' for 5 years given by Zhang et al., (2018) was used to calibrate the parameters of the root distribution model. A preliminary assessment of the root distribution and root growth rates given by Zhang et al., (2018) implies that significant root growth (about 12 percent of the maximum root growth) is observed to a depth of 0.9 meters. Also, it should be noted that the root density is higher at 0.2-0.4 meters, which implies the availability of water for plants at these depth and that the water table fluctuates sharply. Thus a relatively higher root growth window (L=0.5) and α =0.3 is chosen to represent these conditions. A value of 2.0 is chosen for $\frac{\lambda}{\eta}$ to fit the calibration better for the first 5 years. The root growth rate given by Zhang et al., (2018) is input as such in the model for the prediction of the root distribution for the 7 year period. Tron et al., (2015) suggested that the impact of $\theta(z)$ on the root profile is low and for the prediction of root biomass after 7 years a constant value of 1 is assumed throughout the depth.

The parameters of the root distribution model are calibrated with the abovementioned parameters for the root distribution of 5 years. With the calibrated model parameters and growth rates for the 6th and 7th year, a prediction of the root distribution is made. The observed and the predicted root distributions show good conformity, which implies that the adopted parameters and the model are able to capture the root distribution at the location with good accuracy.

To estimate the root distribution in the future, it is necessary to know the temporal increase in maximum root biomass. This parameter will not be known to the designer during the design stages. Thus, like in many soil engineering problems, estimation of maximum root biomass or root growth rate will rely on the experience, understanding and judgement of the designer. Future research needs to be directed in this regards in estimating the growth rate and field data is necessary for the literature. In this case study a steady growth rate of 30 grams per year is assumed for the first 20 years. This assumption falls within the range of minimum biomass of willow root balls



(a) Front view (b) Detailed view of the press dies

Figure 1: Case 1, a 3 meter high stream bank retained by sheet pile made of timber which has low resistance to decay. Case 2, the same stream bank retained by low resistance to decay timber sheet pile-vegetation system. A decayed sheet pile and grown vegetation is shown in Case 2.

reported in Juliszewski et al., (2015). How this assumption of 30 grams per year of root biomass growth and how its variation propagates to the safety of the whole system is out of scope of this article. The root distribution as expected is different from the water limited ecosystems, they don't decrease exponentially with depth, instead show a peak at 0.3 meters. The distribution variation is dependent on vegetation parameters, like the growth rate and hydraulics of water table.

3.2 MECHANICAL STRENGTH MODEL

The root distribution obtained is input into the mechanical reinforcement model. Even though some studies (Smyth et al., 2013) used analytical models to estimate the fine and coarse roots from the total root biomass, they are not used in here due to lack of proof of applicability of these models in all conditions. Hence average tensile strength as used by other researchers (Mickovski and Tardío, 2016; Ollauri and Mickovski, 2014) in analytical modelling is adopted here. An average tensile strength of 32 MPa for Salix alba L. 'Tristis' is input. For this case study the values of k' (Range: close to 1, Thomas and Pollen-Bankhead (2010)) and k"(range: 0.32-1.00, Bischetti et al., (2010)) are assumed as unity.

The variation of the root mechanical strength is shown in Fig 2. The variation of mechanical strength with depth follows the same as the variation of root biomass. The calculated root cohesion of 7 years is more conservative compared with the experimental results obtained by Zhang et al., (2018). The mechanical reinforcement at 20 years due to the plant growth is estimated, see Fig 2.

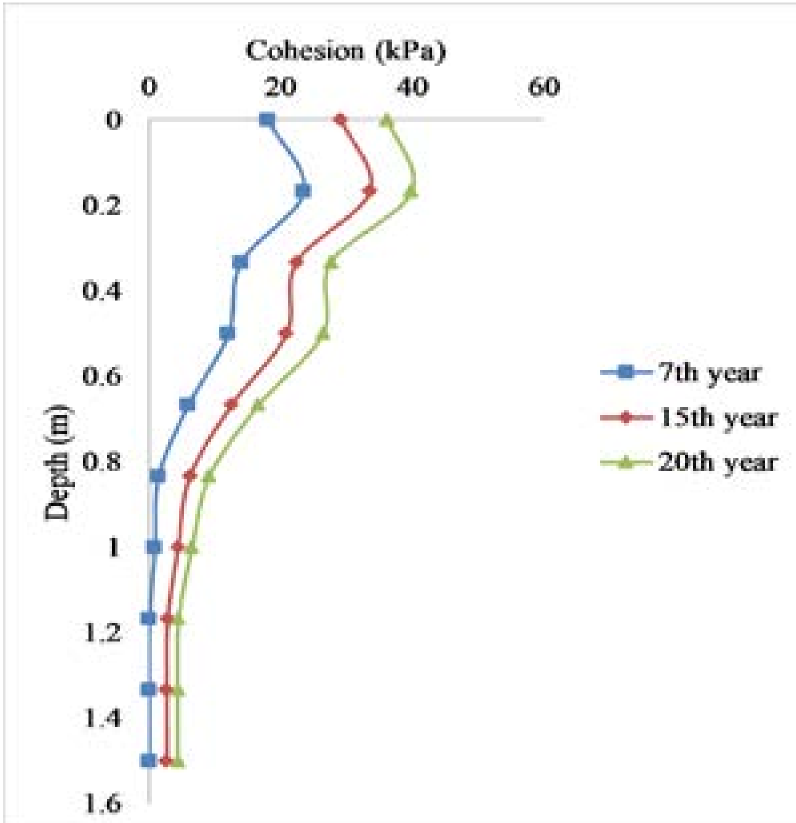


Figure 2: Variation of mechanical contribution of vegetation. Increase in cohesion due to the roots with time is shown

3.3 TIMBER SERVICE LIFE MODEL

The maximum bending moment (M) acting on the sheet pile was taken from the output of D-sheet piling (Visschedijk and Trompille., 2011). This will be the initial bending moment (M_0=21.54kNm) experienced by the sheet pile before the growth of vegetation. Sheet piles are often made of wood species azobé (*Lophiara alata*) which is assigned to strength class D70 of European standard EN 338, (Van de Kuilen and Blass, 2006). This corresponds to a characteristic bending strength of f_m = 49.5MPa after taking into account the safety factors for material property, (γ_M = 1.3 EC5, k_{ls}=1.15) modification factor and a shear strength of 1.5N/mm^2, but excluding the influence of long term loading, as this is now incorporated in the damage model. A sheet pile with width of 1 m, and thickness 0.075 m was chosen to retain the soil. The decay rate of the entire timber sheet pile was assumed to be -0.001 m (1 mm/year). The parameters of the timber damage accumulation model, a=21, b=24.63 were adopted for the estimation of the time to failure line for timber beams (Gerhards and Link, 1987). To estimate the contribution of decayed section modulus, there exist two options. The more conservative approach is to neglect the contribution of the decayed section completely. For more realistic estimation the decayed section can be assumed to have a certain percentage of the initial strength (f_0), (Van de Kuilen, 2007). In this paper two conditions are checked (i) decayed section has a remaining strength f_r which is 20% of the initial strength , f_r=0.2 f_0 (ii) decayed section has no contribution at all: f_r=0.

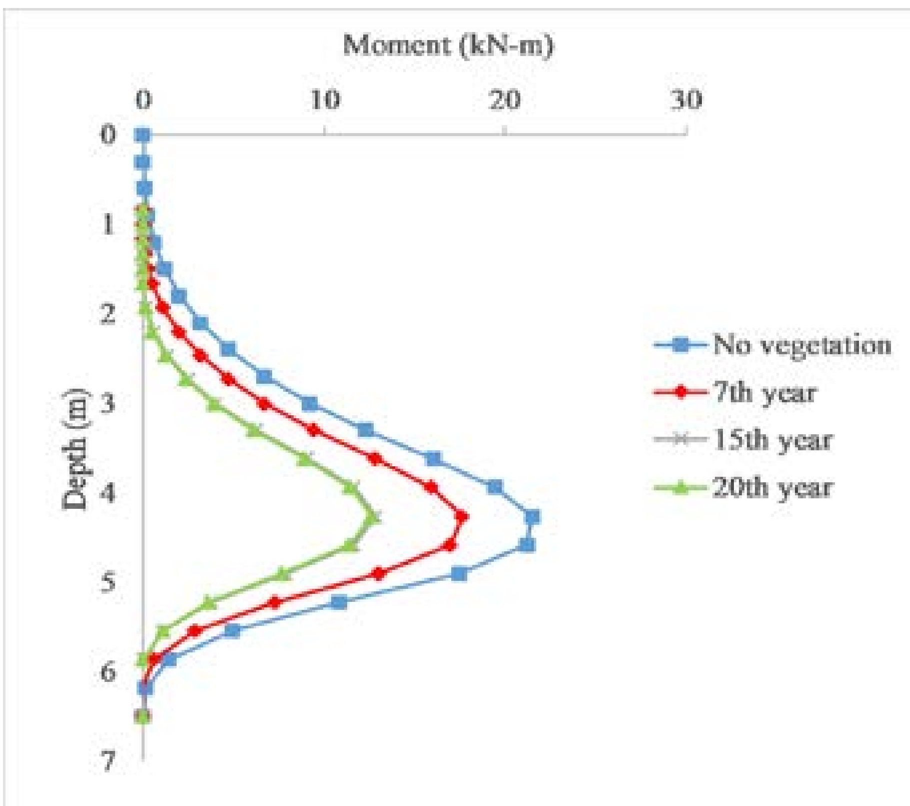
With the assumed decay rate of 1 mm/year, the sectional modulus is estimated to decrease by more than 48% in 20 years. This results in a decrease of moment carrying capacity of the sheet pile. When the decayed area is assumed to have no contribution, the damage coefficient reaches a value of 1 in the 18th year. Thus, the residual moment carrying capacity of the sheet pile system is expected to reduce to zero in 18 years. When the decayed section is assumed to have a remaining strength of 0.2f_0, the damage coefficient reaches a value of 1 in the 23rd year, see Fig 4. Thus when, f_r=0.2 f_0 , it can be seen that complete damage does not occur in 20 years.

The cross sectional area resisting shear reduces by over 28% in 20 years. The residual shear carrying capacity is seen to reduce to zero in 47th year when no contribution of the decayed part is assumed. Under the condition f_r=0.2 f_0, the sheet pile will fail completely by the 59th year (see Fig 4). It can be concluded that the bending moment thus becomes the critical parameter in this case of a design life of 20 years.

3.4 SHEET PILE-VEGETATION SYSTEM

The increase in cohesion was represented as layers of soil of increased cohesion in the stream bank. A total of 10 layers of thickness 0.16 meter each was created and assigned the corresponding cohesion value obtained from the mechanical model. The moment distribution in each year from the 7th year to 20th year was calculated and it can be seen that the moment acting on the sheet pile decreases with the growth of the vegetation. The bending moment without vegetation, Case 1, is 21.54 kNm, reduces to 17.6 kNm in 7 years and further reduces to 12.62 kNm after 20 years (Case 2), see Figure 3. The shear load in Case 1, is 21.44 kN and it reduces to 13.36 kN by 20 years in Case 2. This reduction in bending moment and shear could be included as the time dependent loading in the timber damage model. The new damage coefficient and subsequent residual moment and shear carrying capacity after inclusion of the time dependent loading σ(t) has been estimated. Applying f_r=0.2 f_0, and the new time dependent loading (bending moment and shear), the damage coefficient α at 20 years is 6e-04 in bending and 6e-06 in shear. Further, when f_r =0, the damage coefficient α takes a value of 0.0018 in bending and 7e-06 in shear. This implies that the sheet pile-vegetation system has only very minor damage. As compared to the sheet pile only system, the residual moment and shear carrying capacity of the sheet pile-vegetation system does not reduce to zero in the intended service life of 20 years. In other words, the effect of vegetation is such that a longer service life could be expected.

For instance for the condition f_r =0 the sheet pile-vegetation system is estimated to be damaged completely or the damage coefficient reaches the value of one in 31 years, in case f_r=0.2 f_0 it reaches 43 years in bending. Consequently, a prolonged service life of approximately 13 years and 20 years is expected when the vegetation reinforcement is included in the calculations. In shear an extra service life of 10 years (f_r=0) and 14 years (f_r=0.2 f_0) is expected in a timber sheet pile-vegetation compared to the retaining structure of timber sheet pile alone.



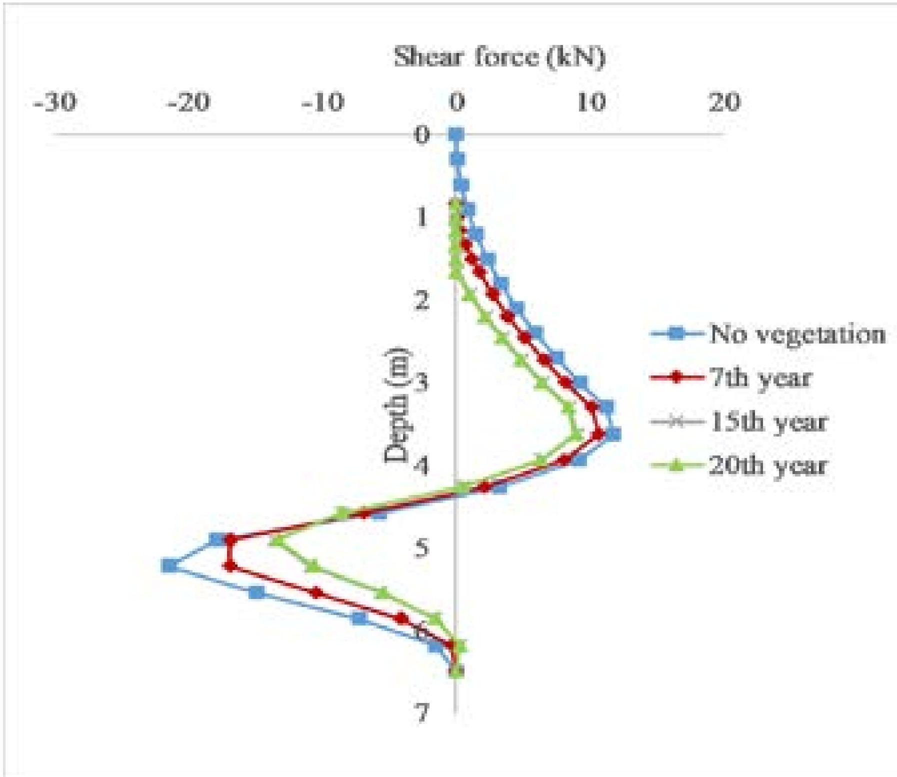
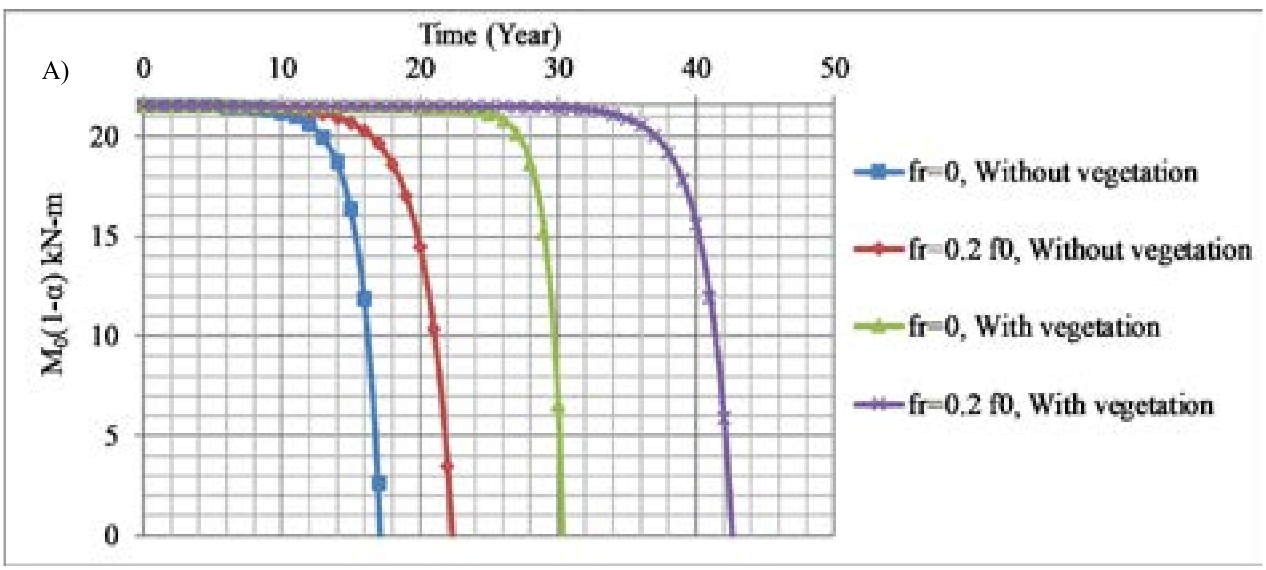


Figure 3: Time-dependent variation of bending moment and shear force acting on the entire length of the timber sheet pile in a timber sheet pile-vegetation system.



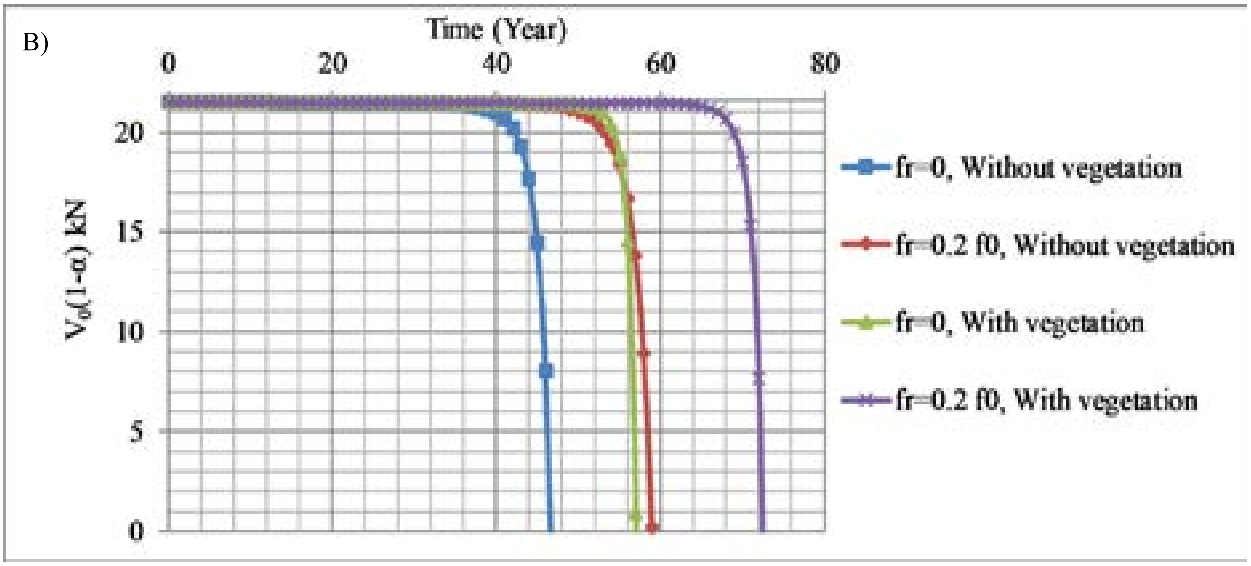


Figure 4: Evolution of damage accumulation on the timber sheet pile with and without vegetation. The variation when a contribution to the resistance is assumed from the decayed section is shown. A) Gives the variation of $M_0(1-\alpha)$ with time due to change in bending moment B) Gives variation of $V_0(1-\alpha)$ with time due to change in shear load

4. CONCLUSIONS

The research in the field of soil bio-engineering is focussed on designing the structure in such a way that the vegetation takes over the inert material like timber in the long term. Realizing the fact that the strength degradation of timber is dependent on the variation of load acting on it with time, an integral model is proposed taking the vegetation development as well as duration of load effects in timber and its biological degradation into account.. With decreasing load acting on the timber sheet pile with the growth of vegetation, the damage accumulation on the sheet pile decreases, thereby increasing the design life of the timber sheet pile. This is illustrated through a case study, where the vegetation is seen to increase the durability of the timber sheet pile by decreasing the load acting on it with time. The system leads to the possibility of designing timber sheet pile walls with smaller dimensions, or with less durable material. The structural safety of the ´combined´ system of sheet pile and vegetation can be estimated using the proposed procedure.

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