

Timber sheet pile-vegetation model for stream bank retaining structure

Abhijith Kamath^{1,*}, Wolfgang Gard¹, and Jan-Willem Van de Kuilen^{1,2}

¹TU Delft, Faculty of Civil engineering and Geosciences, The Netherlands

²TU Munich, Wood technology, Germany

Abstract. Timber sheet piles are widely used to protect canal and stream banks. Quite often, riparian vegetation also grows along these retaining structures. Roots of riparian vegetation mechanically reinforce the soil with their root systems. A timber sheetpile-vegetation model is developed taking into account the mechanical reinforcement of the vegetation roots. The model uses easy to obtain physical parameters, which makes it suitable to have a preliminary estimate of how the forces on the bio engineered structure would evolve.

1 Introduction

In countries like The Netherlands, structurally engineered sheet pile walls are used to protect large parts of the land along the stream banks, about 4000 km [1] of which 60% is estimated to be of timber. One of the negative aspects of artificial stream bank protection techniques is the reduction of riparian zones that were naturally stabilizing the banks. As a natural outcome, valuable habitat and biodiversity has reduced ([2], [3]). Wolter (2001) [2] further reported that even a restoration upto one fifth of the natural stream bank would result in substantial positive effects on the ecology.

By now it is well established that vegetation stabilize the soil, both mechanically [4] and hydrologically [5]. [6] implemented the eco-engineering principles into existing geo-engineering practises through crib wall and live plant system. There has been few attempts to understand the effects of bio-engineering on stream banks, eg. [7]. In a 'composite' retaining structure made of vegetation and conventional retaining wall, the shear strength enhancement by vegetation is expected to reduce the active earth pressure acting on the conventional retaining wall. The dynamic nature of vegetation roots and its effects on the earth pressure acting on a retaining structure has still not been studied well. In this paper, the authors convey the development of a timber sheet pile-vegetation model which could serve as an alternative to the current sheet pile retaining system for the stream banks, see Fig. 1. This new system can be considered as the first step in restoring the unaltered ecosystem and at the same time is sustainable. The dynamic nature of the sheet pile - vegetation retaining structure as a whole and the hydrological effects of the vegetation is out of scope of this paper. As the model is intended to be used by practising engineers and environmentalist for preliminary assessment, the sub-

were chosen depending on current knowledge of parameters.

2 Model framework

The key parameter for determining the required thickness of a sheet pile is the maximum bending moment acting at any depth of the sheet pile. The D-sheet piling software version 18.1 is used for comparison of conventional timber sheet pile and sheet pile-vegetation model proposed in this study. D-sheet piling can check for minimum depth and also overall stability of the sheet piling system. The distribution of moment in the sheet pile before the development of the roots are estimated first. A root distribution model for phreatophytic vegetation given by [8], is used to obtain the vertical root distribution. A modified version of the root cohesion model given by [4] is used to obtain the increase in root cohesion at different depths. The bending moments are estimated again accounting for the new distribution of cohesion with depth. With the advanced root distribution models this method could be extended to know the variation of moment on the sheet pile, with depth & time, due to growth of vegetation. The model flow is shown in Fig. 2.

2.1 Root distribution model

The root distribution model developed by [8] could be used for riparian vegetation which faces oxygen demand when there is high water table and scarcity of water when water table drops. The model takes into account the stochastic variation of the water table as the driving force for the root distribution. It also takes into account the root growth and decay. The analytic model for root distribution provided by [8] is given by the following equation:

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

*e-mail: A.C.Kamath@tudelft.nl

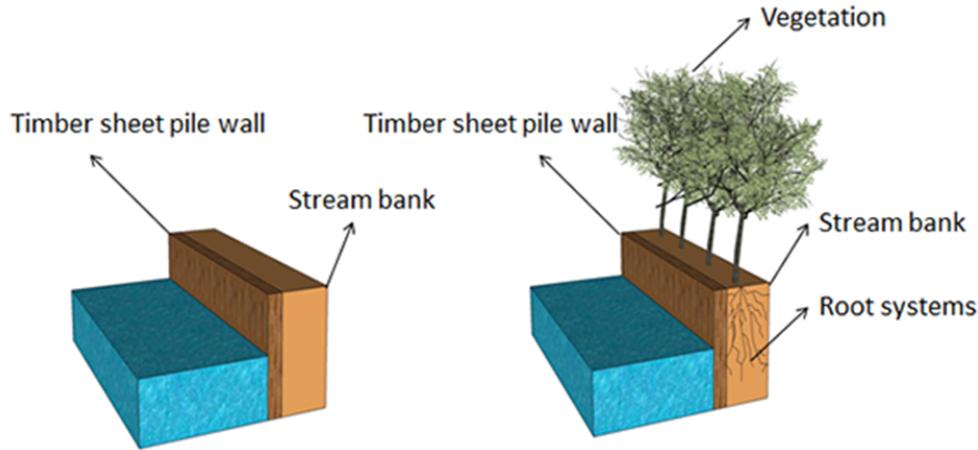


Fig. 1. Left, Case 1: A typical stream bank retaining structure with timber sheet pile. Right, Case 2: Timber sheetpile-vegetation retaining structure after complete growth of vegetation

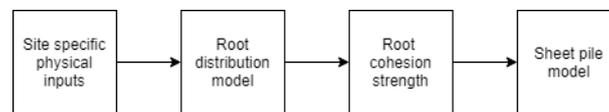


Fig. 2. Sub models and their implementation order in timber sheetpile-vegetation model

$$k(z) = \begin{cases} \Gamma(\frac{\lambda}{\eta}, \frac{h1-z-L}{\alpha}) - \Gamma(\frac{\lambda}{\eta}, \frac{h1-z}{\alpha}), & \text{if } -\infty < z < h1 - L \\ 1 - \Gamma(\frac{\lambda}{\eta}, \frac{h1-z}{\alpha}) & \text{if } h1 - L < z < h1 \end{cases} \quad (2)$$

$$\theta(z) = \frac{\beta(z)}{\gamma} \quad (3)$$

where, $k(z)$ is the probability that a depth z falls in the optimal root growth zone,
 z is the depth,
 $\beta(z)$ is the growth rate of roots, γ is the decay rate of roots,
 λ is the mean rate of increase water table,
 α is the mean depth of pulses,
 η is the decay of the pulses,
 L is the width of the root growth zone,
 $h1$ is the depth of root growth zone.
 $\theta(z)$ is the ratio of growth rate to decay rate of roots.
 For more details about the model, please refer to [8].

2.2 Root cohesion model

The most widely used perpendicular root model, developed by [4] assumes that all roots break simultaneously. The input parameters are the root area ratio and the tensile strength of the roots. Even though this model results in overestimation of the assessed additional cohesion, ([9],[10]) successful application and observation has been reported ([11],[12]). Parameter's k' and k'' were introduced to correct the estimated value from the perpendicular model. k'' is the ratio between perpendicular model and computed Fiber bundle model developed by [9].

$$Cr = k' * k'' * RAR * T \quad (4)$$

where Cr is the estimated root cohesion, RAR is the ratio between cross section area of roots and soil control area, T is the average tensile strength of the roots.

2.3 Sheet pile model

D-Sheet piling 18.1, is a software used widely in The Netherlands for the design of retaining walls, especially sheet piles. With few geotechnical input parameters, D-sheet piling uses the Bishop slip circle to estimate the overall stability of the system. It uses a graphical interactive interface and calculates the maximum bending moment and shear force required for the design thickness of the sheet pile. From the root cohesion model it is possible to estimate the increase in cohesion at different depths due to the vegetation roots. To account for this, in D-sheet piling, the retained soil is divided into different layers of increased cohesion.

2.4 Model Implementation-Illustration case study

There is a relative scarcity of studies focusing on growth of roots in riparian zone with time, when compared to forest or hill slope ecosystems. However the experimental study conducted by [13] could form an excellent base for the implementation of the sheet pile vegetation model developed in this study. [13] reported the spatio-temporal variation of root morphology of *Salix alba* 'L.Tristis' at a river bank in Liuli river in the Huairou district, China. The root biomass was measured after 1, 5 and 7 years after planting the saplings. Sandy loam with small gravel was reported at top 0-0.4m and below that, loamy sand with gravel was found. This case study is chosen due to detailed results on the root

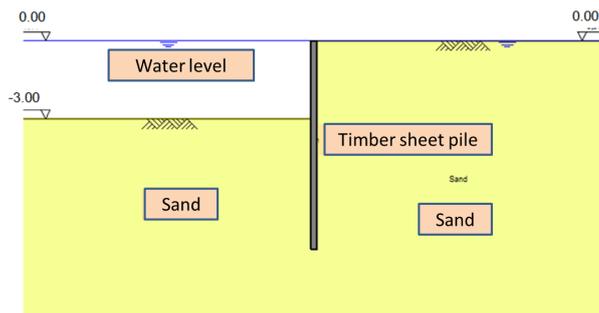


Fig. 3. Illustration case study example. A 3 meter river bank supported by a timber sheet pile of depth 6.50 m and elastic stiffness 783 kNm²/m with no anchor. Cohesion of soil and internal friction angle before the growth of vegetation are taken as 0 kPa and 30° respectively.

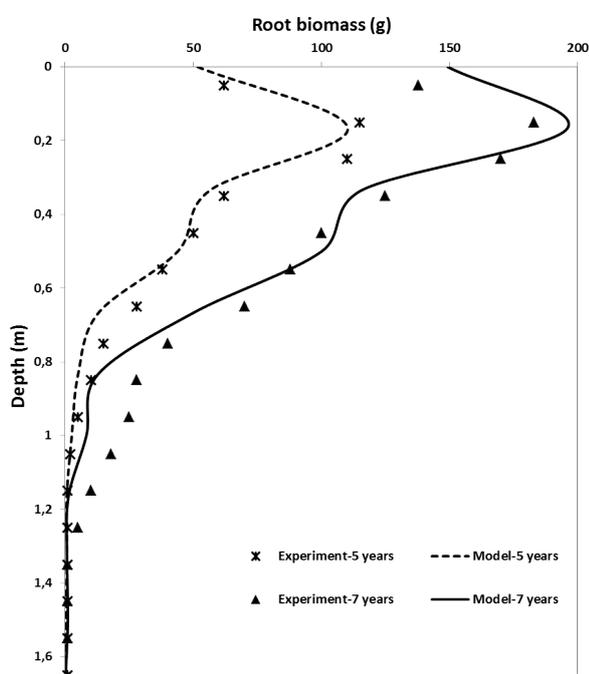


Fig. 4. Measured and modeled vertical root distribution. The lines are the modeled distribution, while the symbols represent the measured profiles. The star symbol was used for calibration and dashed line is the model prediction for 5 years. Thick line is the prediction for 7 years while triangle symbols represent the measured values for 7 years. $\alpha = 0.3$, $L = 0.5$, $h1 = 0.8$, $\lambda = 0.0667$, $\eta = 0.033$. For the growth rates refer to [13]

growth with time which enables for calibration and validation of the root distribution model and the time dependent consequences for the design of the sheet pile. Also, the soil conditions suit the use of the root distribution model adopted. Sheetpile-vegetation model for the protection of this river bank (assuming a typical depth of river bed and same soil properties to extend to subsoil) is illustrated in this case study. Values of parameters are given in the Fig. 3.

3 Results & Discussions

In case 1, where there are no roots, to retain 3 meters of sand with an internal friction angle of 30°, a 6.5 meter long sheet pile wall is designed using D-sheet piling program. The maximum bending moment of 21.54 kN/m will act at a depth of 4.26 meters. The maximum lateral displacement obtained is 247 mm and as expected it was on the top because no anchor is provided. The root distribution model was calibrated with the experimental results for 5 years. The parameters used are given in Fig. 4. The calibrated model was used to predict the root distribution after 7 years. The model is able to capture the root distribution after 7 years. The model underestimates the root mass below 0.8 meters. This can be due to the lower root growth window chosen for calibrating the model. For future predictions the ratio of growth rate to decay rate was chosen to be the same hence $\theta(z) = 1$. Root biomass was assumed to increase by 30g/year for 30 years. Note that the very small value of root biomass increase is assumed to get conservative results. Also, with more field data, better estimates of root biomass and hence the root cohesion could be obtained. Root growth for 30 years was fed into the root cohesion model. The perpendicular model was used to predict the variation of cohesion for 30 years with depth. In case 2 where there are roots present, the retained soil was divided into 10 layers up to a depth of 1.6 meters, which is the maximum depth of root growth that was predicted by the root distribution model. The cohesion values obtained from the root cohesion model, are assigned to these layers to account for the cohesion increase due to vegetation. The dimensions and properties of the sheet pile were not changed. The new variation in the moment with depth is given in the Fig. 5. The maximum bending moment acting on the sheet pile reduced to 12.7 kN/m. The lateral displacement of the sheet pile on the top reduced to 120 mm. With specialized root distribution models like the [8] and with extensive site experimental data like [13], it has become possible to incorporate the positive effects of vegetation in stream bank retaining structures. The base model presented in this article is based on relatively easy to obtain physical parameters. Sheet pile thickness is designed based on maximum moment to be resisted by the sheet pile. From Figure 5, the reduction in moment in

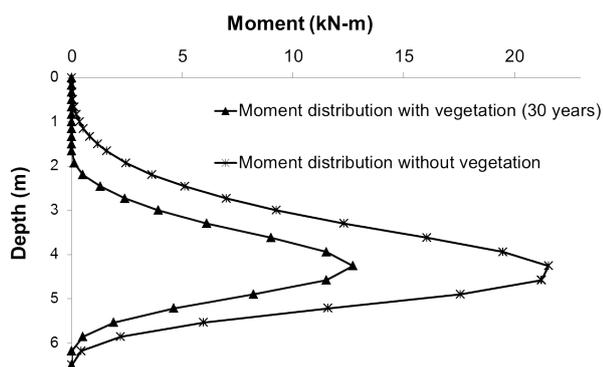


Fig. 5. Variation of moment including the effect of vegetation with time.

the sheet pile implies that by including vegetation effects on retaining structures, the factor of safety increases, for instance, in this example, the factor of safety increases by 41%.

4 Conclusions

The methodology used here could be further extended to design a bio-engineered stream bank retaining structure. The reduction in moment to be supported by the wooden sheet pile could be potentially be exploited. For example, instead of using hardwoods which are more resistant to decay, locally available softwoods, which are susceptible to decay could be used for the stream bank applications. With decay the sheet pile would be able to resist less moment, which could be supported by vegetation roots as in this example. Such a synergy can be designed in a bio engineering framework with better knowledge of timber decay models and root growth models. The vegetation induces positive hydraulic stresses on the soil. Hence it is worthwhile to include the temporal variation of suction induced by the vegetation roots in the calculations. More research is required to characterize the root distribution of riparian plants in different types of soil. A more generalized model including the hydro logical effects, decay of timber and root distribution of vegetation in clay is the need of the hour.

The authors wish to acknowledge the support of the European Commission via the Marie Skłodowska-Curie Innovative Training Networks (ITN-ETN) project TERRE 'Training Engineers and Researchers to Rethink geotechnical Engineering for a low carbon future' (H2020-MSCA-ITN-2015-675762).

References

- [1] J.W. van de Kuilen, M. L R Van Der Linden, *New Zealand Timber Design Journal* **1**, 11 (1999)
- [2] C. Wolter, *Landscape and Urban Planning* **53**, 135 (2001)

- [3] E. Hurst, M. Hehnke, C. Goude, *American Birds* **34**, 8 (1980)
- [4] T. Wu, Civ. Eng. Dep. Ohio State Univ., Columbus, Ohio, USA (1976)
- [5] N. Pollen-Bankhead, A. Simon, *Geomorphology* **116**, 353 (2010)
- [6] G. Tardío, S.B. Mickovski, *Ecological Engineering* **92**, 138 (2016)
- [7] L. Anstead, R.R. Boar, N.K. Tovey, *Area* **44**, 479 (2012)
- [8] S. Tron, P. Perona, L. Gorla, M. Schwarz, F. Laio, L. Ridolfi, *Geophysical Research Letters* **42**, 7098 (2015)
- [9] N. Pollen, A. Simon, *Water Resources Research* **41**, W07025 (2005)
- [10] R.E. Thomas, N. Pollen-Bankhead, *Ecological Engineering* **36**, 47 (2010)
- [11] S. Mickovski, P. Hallett, A. Bengough, M. Bransby, M. Davies, R. Sonnenberg, *Advances in GeoEcology* **39**, 247 (2008)
- [12] A. González-Ollauri, S.B. Mickovski, *EQA-International Journal of Environmental Quality* **13**, 37 (2014)
- [13] D. Zhang, J. Cheng, Y. Liu, H. Zhang, L. Ma, X. Mei, Y. Sun, *Forests* **9**, 493 (2018)