A study on deterioration and residual service life of recovered azobé (Lophira alata) sheet piles

Kamath, Abhijith; Mirra, Michele; Ravenshorst, Geert; van de Kuilen, Jan Willem

DOI
10.1007/s00107-025-02283-3

Publication date
2025

Document Version
Final published version

Published in
European Journal of Wood and Wood Products

Citation (APA)
Kamath, A., Mirra, M., Ravenshorst, G., & van de Kuilen, J. W. (2025). A study on deterioration and residual service life of recovered azobé (Lophira alata) sheet piles. *European Journal of Wood and Wood Products*, *83*(4), Article 129. https://doi.org/10.1007/s00107-025-02283-3

European Journal of Wood and Wood Products (2025) 83:129
https://doi.org/10.1007/s00107-025-02283-3

ORIGINAL ARTICLE

A study on deterioration and residual service life of recovered azobé (*Lophira alata*) sheet piles

Abhijith Kamath[1] · Michele Mirra[1] · Geert Ravenshorst[1] · Jan-Willem van de Kuilen[1,2]

Received: 1 December 2024 / Accepted: 30 May 2025

Abstract

Large parts of banks of canals in the Netherlands are protected by azobé timber sheet piles. Many kilometers of sheet piles in the province of Noord-Holland, are planned to be replaced or to undergo maintenance. Yet, there is insufficient knowledge on the current state of the azobé sheet piles and their residual service life. Based on this, a series of investigations on azobé sheet piles after 57 years of service were performed. Visual inspections showed surface deterioration on the water-exposed side for all boards. Nondestructive testing using micro drilling technique showed no signs of internal deterioration. A maximum reduction in thickness of 17% and an average thickness reduction of 6.7% of original thickness were observed. CT scanning showed that the remaining cross sections of the azobé boards were intact and had comparable density of new azobé boards. An exponential damage accumulation model was used to predict the residuals service life of the timber sheet piles subjected to earth stress. Conservative estimates based on physical measurements and residual bending strength indicate that the sheet piles have an additional service life of 22–43 years from the current state.

1 Introduction

The banks of canals in the Netherlands have been traditionally protected by timber sheet piles. The sheet piles have one side facing the earth and the other side facing water (Fig. 1a). The top part of the sheet piles has an air-water-soil interface, susceptible to decay due to favourable environment for microorganisms. The part which is submerged in water is relatively less susceptible to decay, primarily due to lack of dissolved oxygen required for microorganisms. Nowak et al. (2019) confirmed the above engineering intuition about variation of degradation along the sheet pile, in their study on wharf timber sheet piles after 70 years of service. In the Netherlands, individual wooden sheet pile boards are connected using tongue and grove connection in accordance with EN 5493 (2010). Timber sheet piles are either cantilevered or anchored and kept permeable to prevent differences in water levels between ground and canal.

Timber sheet piles made of azobé (*Lophira alata*) gained traction after the second world war as a durable alternative to other wood species such as Oak and treated pine. Azobé shows high resistance to acidic conditions and weathering (Wood Handbook 2010). Knot ratio governs the strength for softwoods, while dense (tropical) hardwoods, including azobé, have little or no knots, and slope of grain governs the strength. Practically, slope of grain is difficult to determine, henceforth azobé is assigned into a single visual grade in accordance with EN 16737 (2016) and classified in strength class D70, as listed in EN 1912 (2012) (Wesselink and Ravenshorst 2008; Ravenshorst et al. 2020).

Even though widely used, there is little information available on current state and residual service life of azobé sheet piles that are in service. Van de Kuilen and Blaß (2005) conducted four-point bending tests on azobé boards which were in service for 15–18 years. The average modulus of rupture and global static modulus of elasticity obtained in their study were > 106 MPa and > 17,000 MPa respectively. It is to be noted that the strength parameters obtained for old boards in Van de Kuilen and Blaß (2005) had higher values than new azobé boards reported by same authors.

Apart from the residual strength, there is also lack of information about the decay and deterioration of azobé

✉ Abhijith Kamath
A.C.Kamath@tudelft.nl

[1] Department of Engineering Structures, Biobased Structures and Materials Group, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands

[2] Wood Technology, School of Engineering and Design, Timber Research Munich, Technical University of Munich, Winzererstrasse 45, 80797 Munich, Germany

Fig. 1 Full size azobé sheet piles (**a**) in service at Delftse hout, Delft, The Netherlands; (**b**) pulled out after 57 years of service from Medemblik, the Netherlands

boards after decades of service in in-ground applications. Nowak et al. (2016) suggested that resistance drilling has potential to be used to qualitatively asses the depth of wood decay in existing timber structures. Micro-drilling has been effectively used for evaluating the conditions in existing above ground structures (Ceraldi et al. 2001; Lechner et al. 2014; Brunetti et al. 2023) and below-ground wooden structures (Pagella et al. 2024; Mirra et al. 2024). Another non-destructive technique used to assess the wood structure and pattern of degradation is to analyse thin sections using a light microscope under polarised light (Klaassen. 2008; Björdal and Elam 2021; Humar et al. 2021). Based on visual inspection and density profiling, Klaassen and Creemers (2020) found 'little decay' in freshwater hydraulic structures made of azobé, such as sheet piles, free water poles, and landing stages.

Within the Netherlands, the replacement of significant portions of timber sheet piles is planned for the next decade due to the conclusion of their service life or as a result of visual inspections conducted by divers. In a first work, Kamath et al. (2025) analysed a sample of azobé sheet piles, extracted from *Provincie Noord-Holland* after 57 years of service, to assess their mechanical strength properties for potential reuse. The present study was initiated in response to a requirement from *Provincie Noord-Holland* for a comprehensive evaluation of decay and deterioration, as well as a prediction of the residual service life of the existing azobé sheet pile walls (Fig. 1b). This detailed assessment is necessary for the effective planning of maintenance and replacement activities for the existing azobé sheet pile infrastructure. Consequently, the focus of this study is to assess the degree of deterioration and decay present in existing azobé sheet piles and its influence on their residual service life. To this end, in addition to the non-destructive evaluation of deterioration conducted in this study, the mechanical strength characteristics obtained in Kamath et al. (2025) will be used in combination with the damage accumulation model developed by Van de Kuilen (2007).

2 Materials and methods

2.1 General

Azobé sheet piles from near Medemblik, the Netherlands, were being replaced with steel sheet piles. Consequently, a batch of azobé sheet piles extracted from this site were used in this study. The delivered sheet piles were processed into

1 m long boards, yielding two boards per sheet pile representing the top and bottom portions. It is important to note that sheet piles in the Netherlands are typically used in perpetually wet environments due to the country's extensive and well-maintained canal system. Therefore, the prepared boards were submerged in water for more than six weeks before testing to accurately reflect these service conditions.

A multiscale approach similar to the assessment of other wooden structures in in-ground application was utilized in this study (Mirra et al. 2024; Klaassen 2008). Several methods for assessing the state of the boards and further estimation of service life were adopted: non-destructive analysis was performed with visual assessment, micro-drilling measurements, computed tomography (CT) scans and microscopic analysis. A summary of four-point bending test results on the recovered azobé sheet piles given by Kamath et al. (2025) is briefly discussed and further combined with damage accumulation model Van de Kuilen (2007).

2.2 Experimental campaign

A visual assessment was conducted on the recovered boards. Evaluation were primarily conducted to evaluate any observable surficial deterioration or decay holes. Micro-drilling measurements were performed with an IML-RESI Power Drill with feed speed of 25 cm/min and drill speed of 5000 r/min. Measurements were taken from both water facing side and earth facing side of the recovered timber board. Drilling and feed resistance were recorded to evaluate any internal decay.

CT scans were performed on 22 selected boards, comprising both top and bottom boards. The representative pictures obtained from the CT scans were analyzed through *myVGL* 2022 software (Volume Graphics 2022). As a final step in evaluation of deterioration of the recovered azobé boards, light microscopy analysis was conducted on radial and tangential slices manually cut from both top and bottom boards. In addition, full boards were observed under the microscope. To conduct these investigations, a Keyence VHX 6000 digital microscope was adopted.

2.3 Service life modelling

A damage model including the effects of time-dependent loading and resistance with changing cross sections given by Van de Kuilen (2007) was used (Eq. 1) to assess the time to failure of the azobé sheet piles.

$$\frac{d\alpha}{dt} = \exp\left(-a + b\frac{\sigma(t)}{f(t)}\right) \tag{1}$$

Where a and b are constants, $\sigma(t)$ is the stress acting over time and $f(t)$ is capacity of the material with time, α is the damage factor, which takes the value of $0 \leq \alpha \leq 1$. Failure will occur when α takes value of 1. When the value of α is in between 1 and 0 the structure is able to support the estimated load. Thus, from the above damage accumulation model the residual service life and damage accumulation on the sheet pile in this study can be estimated.

The change in cross section due to deterioration results in slow reduction in moment carrying capacity. From the experimental program it was determined that the primary deterioration on the sheet pile was due to erosion on the water facing side, which results in a decrease in cross section of the sheet pile. Reduction in width of the sheet pile was seen to be minimal. Therefore, reduction in cross section solely due to reduction in thickness is here taken into account. Thus, no strength contribution due to the deteriorated cross section is included. The total change of resisting sectional modulus can be determined as:

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

where δ is the rate of decay per year, h is the thickness of the sheet pile and t is the time. Thus, the sectional modulus W_t could be written in terms of original sectional modulus W_0 as:

$$W_t = W_0 \in_I (t) \tag{3}$$

The strength of recovered azobé boards from four-point flatwise bending tests conducted on the 152 boards according to EN 408 (2010) for determining the bending strength and modulus of elasticity reported by (Kamath et al. 2025) were used as the basis for current strength in the above model for estimating future service life.

3 Results and discussion

3.1 Results from experiments

The deterioration of the recovered boards were seen to be non-uniform with respect to the face of the sheet pile. Sheet piles in service have a water-facing side and a soil-facing side. Erosion deterioration was observed in all boards throughout the length on the water side during visual assessment. Decay holes, resembling marine borer (*Teredo navalis*) attack passing through the full length of the sheet pile were observed in approximately 10% of the total boards analysed (Fig. 2). No visible deterioration was observed on the soil facing side. This outcome was also confirmed in

Fig. 2 Detrioration on water side (**a**) and earth side (**b**), with arrows highlighting the holes due to marine borer attack

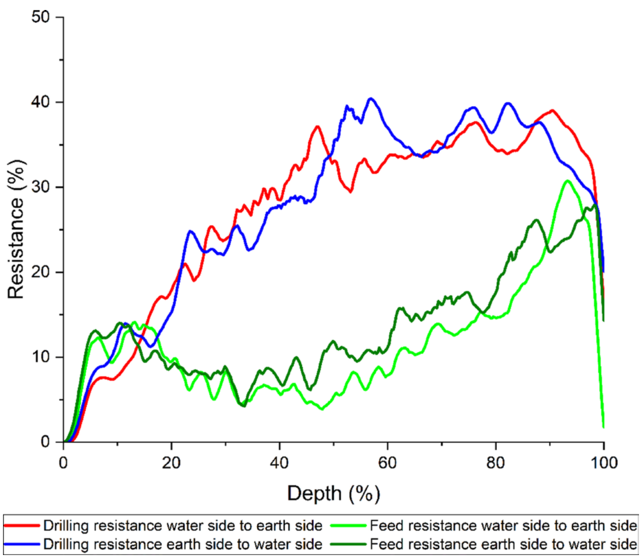

Fig. 3 Drill and feed resistance from micro-drilling measurements exectued from water side to earth side and vice versa

the boards selected for CT scanning and microscopic analysis. Since azobé is graded into a single strength class based on slope of grain measurements (Ravenshorst et al. 2020), the observed deterioration further hinders the classification/rejection of the recovered boards. According to Gard and van de Kuilen (2018), while visual assessment can identify surface-level defects in wood, it fails to identify critical internal characteristics like cracks, the presence of juvenile and intermediate wood, and biological decay. In addition, the existing visual strength grading standards may not properly grade recovered timber (Llana et al. 2023). Further, Llana et al. (2024) proposed that instead of assigning to a strength class, recovered wood should be described on the basis of grade determining properties such as strength, stiffness, density, indicators for bending or tension and secondary property profiles. Hence, in this study, in addition to the visual assessment, a comprehensive evaluation using micro-drilling, CT scans, microscopic analysis was performed, complemented with results from four-point bending tests reported by Kamath et al. (2025).

Resistance penetration drilling did not show any internal deterioration in the boards when drilled from earth side to water side and vice versa (Fig. 3). This proved to be true for both drilling and feed resistance (Fig. 3), with profiles very close to each other. Even though no direct comparison of micro-drilling measurements from new azobé boards was possible, those conducted at locations along the sheet piles which were embedded in soil with no deterioration, were similar to other parts of each board. Thus, the detected erosion on the boards, leading to a reduction in cross-sectional area, seemed to be limited only to their surface. Gard and van de Kuilen (2018) suggested that micro-drilling resistance testing on azobé can reveal not only defects like decay and cracks but also differences in density arising from slow growth and the presence of juvenile wood. They stressed that this detection capability is contingent upon precise calibration of the drilling, taking into account the depth, the wood's cross-sectional area, and the inherent characteristics of the wood species. Micro-drilling has been successfully used for assessing the decay in the outer layer of foundation piles in Amsterdam (Pagella et al. 2024) and proved to give useful insights into waterlogged piles (Humar et al. 2021). However, in this study no such decay or differences in density could be clearly detected, an outcome confirmed by the performed CT scans. Figure 4 shows an example of board featuring the aforementioned erosion in combination with marine borers attack, as well as an example of sound board. Interestingly, in spite of deterioration and long service life, the remaining cross section of the tested boards

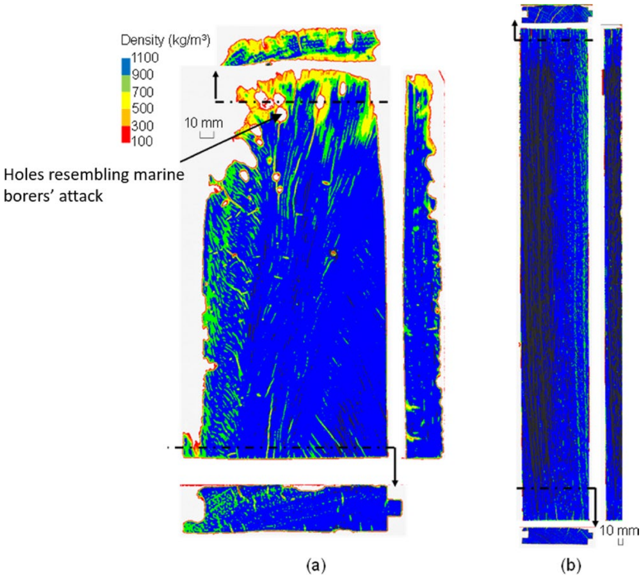

Fig. 4 Results from CT scans on a decayed part of the board located on top water facing side (**a**) and sound part of the board located at bottom water facing side (**b**) Arrow indicates decay holes resembling marine borer attack

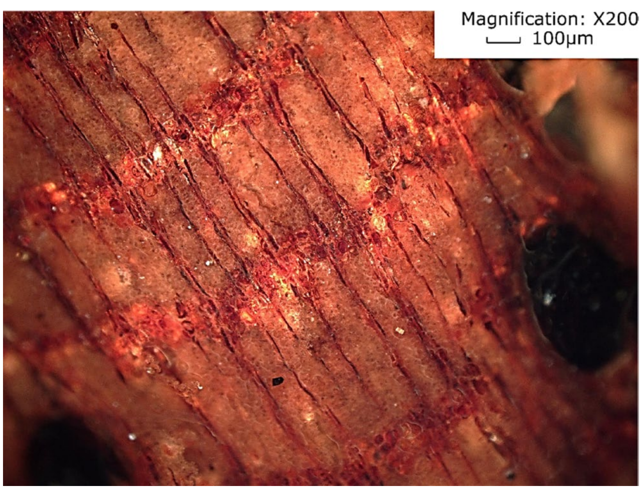

Fig. 5 Example of radial section taken from the eroded portion of a board, with no apparent sign of severe degradation

had densities comparable with those of fully sound azobé, underpinning the outcomes of micro-drilling measurements.

Slices from intact and deteriorated parts showed a similar structure in microscopic analysis (Fig. 5). However, when the full boards were analysed on the water-facing side, fungi colonies resembling worm-spored wax cup (*Orbilia aurantiorubra*) were detected, see Fig. 6. This may be an

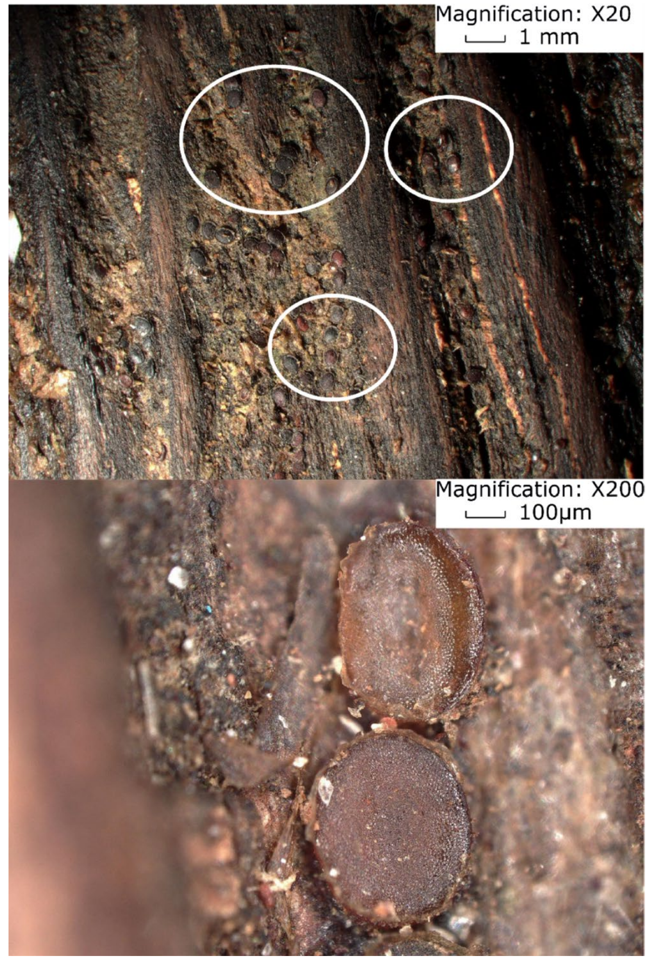

Fig. 6 Fungi resembling worm-spored wax cup (Orbilia aurantiorubra) detected under microscopic analysis on the water-facing surface of a board

indication of slow fungal decay process in progress, since the observed micro-organisms are known to be usually secondary colonisers found in hardwoods. While these fungi primarily thrive in moist, organic-rich environments, their specific effects on highly durable hardwoods like azobé remain less studied. Azobé's natural resistance to decay likely limits *Orbilia*'s direct impact, although it may appear in later stages of degradation if the wood is compromised by more aggressive decay agents.

The main outcomes of the four-point bending tests reported by Kamath et al. (2025) are given in Table 1. The boards were classified into D50 according to EN 338 (2016) with modulus of elasticity as governing parameter. Five-percentile bending strength using parametric and

Table 1 Average values of dimension and strength parameters obtained from four point bending tests reported by Kamath et al. (2025)

No. boards	Length (mm)	Thickness (mm)	Width (mm)	S/T	Density(kg/m^3)	MC (%)	$MOE_{s,g}$ (MPa)	MOR (MPa)
152	1000.3 (0.7)	36.9 (3.9)	192.7 (22.2)	20.3	1090 (4.5)	38 (19.7)	11,500 (21.2)	78.8 (21.1)

S/T span to thickness, *MC* moisture content, MOR Bending strength, $MOE_{s,g}$ global static modulus of elasticity. Coefficient of variation in % is given in brackets

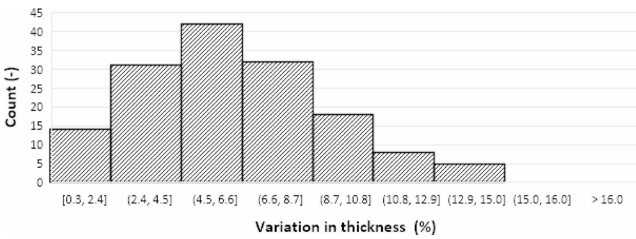

Fig. 7 Distribution of variation in thickness obtained comparing most intact part of the sheet pile with least intact part of the sheet pile

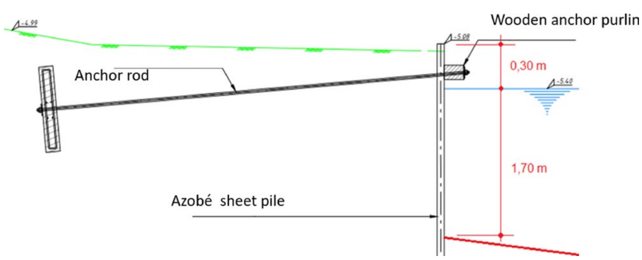

Fig. 8 Cross section of azobé sheet pile with a retaining height of 2 m, Taken from (Kamath et al. 2025)

Table 2 Input parameters used for D-sheet pile model for estimating the load acting on the Azobé sheet pile after installation

Parameter	Value	Reference
Soil cohesion	0 kPa	Assumed
Soil friction angle	40°	Assumed
Unsaturated unit weight	18 kN/m^3	Assumed
Saturated unit weight	20 kN/m^3	Assumed
Length of sheet pile	3 m	Measured
Modulus of elasticity	16,000 MPa	Literature (Van de Kuilen and Blaß 2005)
Thickness of sheet pile	40 mm	Measured
MOR characteristic	70 MPa	Literature (EN 5493 2010)

non-parametric methods were 60 MPa and 58 MPa according to EN 384 (2016). The reduction in cross-sectional thickness was determined by measuring the most intact part of the sheet pile and least intact part of the sheet pile, see Fig. 7. Typically, bending loads govern the behavior of timber sheet piles used for bank protection; consequently, only bending test results were used in this study and the damage accumulation model.

4 Service life estimation

4.1 Loading on sheet pile

The sheet piles investigated in this study were designed for a soil-retaining height of 2 m (Fig. 8). The soil profile of the location included different layers of sand, silt and clay. Since little knowledge is available about the soil strength parameters, the ones given in Table 2 are assumed. Average sheet piles' length was 3 m and they were anchored at a depth of 0.30 m. The anchored sheet pile system was analysed in D-sheet piling software version 18.1. Analysis using partial factors prescribed in "EuroCode 7, Part 1: General rules" (NEN-EN, March 2005) resulted in the sheet pile system having a stability factor of 2.4, thus stable according to Bishop method. The maximum bending moment of 4.7 kNm was obtained at a depth of 1.56 m. Similarly, maximum shear force of 7.37 kN was obtained at a depth of 0.3 m. The bending stress of 17.5 MPa based on the original cross section indicates a very low stress level, of 17.5/78.8 = 22.2%, neglecting any load sharing effects.

The damage accumulation from the current state to future is estimated. At current state the thickness of the sheet pile is taken as to be decreased by 17% of the original thickness, which is the maximum thickness reduction observed in the tested azobé boards. Thus, the current thickness of the boards was taken as 33 mm. With frequent change in water levels, macro- and micro-climate changes, changing pattern in the usage of canals, an accurate estimation of reduction in cross section is not possible. Hence, three different levels of decay rate are taken from the current thickness, a reduction of total of 1%, 0.75% and 0.5% in thickness per year is assumed. It has to be noted that decay rate is expressed in % of thickness is used only for reference and cannot be applied directly to boards of different thickness. Thus, the decay rate used in this study would correspond to 0.33 mm/year, 0.24 mm/year, 0.165 mm/year.

In addition to the decrease in thickness, bending strength influences the moment carrying capacity of the sheet pile. While azobé timber is generally classified in D70 class, the boards tested in this study were seen to have lower strength. The source or initial strength of azobé boards when initially placed in service is unknown. Thus, whether the reduced strength is due to damage accumulation or biological deterioration during the service life or if it falls within the natural scatter of the material itself, cannot be predicted. Crews and Mackenzie (2008) reported a general reduction in bending strength in recycled hardwood timber compared to new timber.

For predicting the future damage accumulation, azobé board strength corresponding to D55, D60 is considered. While full damage is accumulated when $\alpha = 1$, an interim value of alpha could be taken for planning any maintenance and intervention. A limit value of $\alpha = 0.2$ is assumed as time for any intervention. The variation of damage accumulation on the sheet pile for D60 and D55 is shown in Fig. 9 for an acting bending moment of 5 kNm. It can be seen that an intervention would be required in 22 years, when a sheet pile strength D55 and a 1% decay rate (0.33 mm/year) is taken. The time for maintenance and intervention increases to 43 years when decay rate is 0.5% of the current thickness.

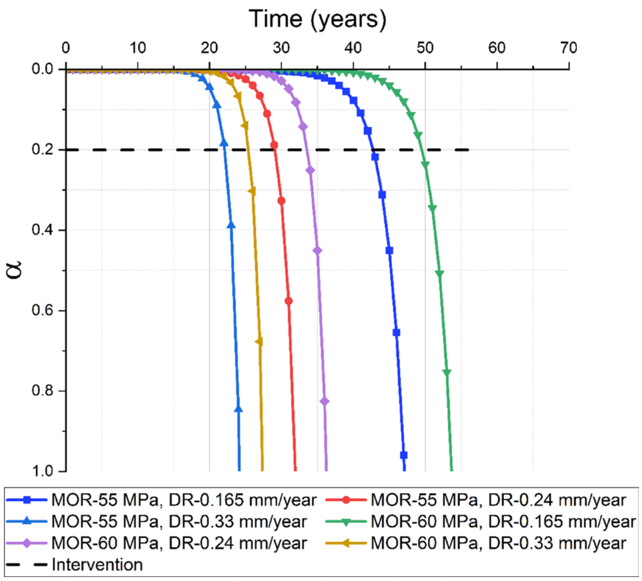

Fig. 9 Damage accumulation with bending strength of 55 MPa and 60 MPa. DR- decay rate in mm/year

When the strength of the material is taken as D60 and a 0.33 mm/year, 0.24 mm/year, and 0.165 mm/year decay rate is considered, intervention would be necessary at 25, 34, and 49 years, respectively (Fig. 9).

4.2 Practical implications

Large parts of bank protection in different provinces in the Netherlands are currently being replaced. One of the reasons for the intervention is due to excessive out-of-plane displacement observed. This could be due to the loss of support at anchorage or due to deterioration of the sheet pile itself. However, there is lack of knowledge about the current condition of the sheet piles and their residual service life. The recovered azobé sheet piles showed minimal decrease in cross-sectional thickness (max 17%) in 57 years, which would amount to less than 0.5% decrease in cross section per year. From the damage accumulation study above, with conservative estimates of deterioration, up to 1% reduction of current thickness per year, the recovered sheet piles could be reused to protect the same free height of bank, for an additional minimum of 22 years. It has to be noted that the condition of anchorage is not known and surcharge loading is not taken into account. Also, increase in strength as a result of the system effect, load sharing factor of 1.17 on the fifth-percentile strength (Van de Kuilen and Van Der Linden 1999) was not taken into account, which makes the current approach conservative.

5 Conclusion

Damage accumulation predictions on recovered azobé timber sheet piles were conducted. Visual inspection have demonstrated that primary form of deterioration observed was superficial, due to erosion decay. No interior deterioration was observed on timber boards based on the density determined from CT scans and the signals from micro-drilling measurements. Four-point flatwise bending tests showed that the azobé boards had a characteristic bending strength of 58–60 MPa based on parametric and non-parametric classification. Thus, for damage accumulation predictions, deterioration was considered as decrease in cross section due to thickness reduction. Conservative estimates show that the residual lifetime for any maintenance and intervention action would be a minimum of 22 years.

The results of this study can be adopted as basis for further research in terms of material and mechanical characterisation, reuse potential, as well as maintenance and replacement planning of (tropical) hardwood sheet piles, promoting the use of sustainable and nature-based solutions for protecting canal banks.

Acknowledgements The authors gratefully acknowledge the Provincie Noord-Holland and Centrum Hout for having funded the research study. A final acknowledgement to Ganesh Shri Raam Kalaichelvi Senthil Kumar for performing the experimental tests.

Author contributions A.K and M.M conducted the experiments and prepared the manuscript. Plots 4-5 was done by M.M and rest of the plots were done by A.K. G.R provided methodology and analysis background. J.W.K obtained the funding and materials for research, supervision, planning and reviewed draft manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Björdal CG, Elam J (2021) Bacterial degradation of nine wooden foundation piles from Gothenburg historic City center and correlation to wood quality, environment, and time in service. Int Biodeterior Biodegrad 164:105288

Brunetti M, Aminti G, Vicario M, Nocetti M (2023) Density Estimation by drilling resistance technique to determine the dynamic modulus of elasticity of wooden members in historic structures. Forests 14(6):1107

Ceraldi C, Mormone V, Russo Ermolli E (2001) Resistographic inspection of ancient timber structures for the evaluation of mechanical characteristics. Mater Struct 34:59–64

Crews KI, MacKenzie C (2008) Development of grading rules for recycled timber used in structural applications. In: World Conference on Timber Engineering. WCTE

EN 408 (2010) EN 408:2010+A1:2012. Timber structures. Structural timber and glued laminated timber. In: Determination of some physical and mechanical properties. CEN, Brussels

EN 16737 (2016) Structural timber. Visual strength grading of tropical hardwood. CEN, Brussels

EN 338 (2016) Structural timber. Strength classes. CEN, Brussels

EN 1912 (2012) Structural timber—strength classes—assignment of visual grades and species. CEN, Brussels

EN 384 (2016) Structural timber—determination of characteristic values of mechanical properties and density. CEN, Brussels

Gard WF, Van de Kuilen JWG (2018) Micro-drilling resistance measurements of dense hardwoods for hydraulic structures. In: WCTE-World Conference on Timber Engineering, Seoul, South-Korea

Humar M, Balzano A, Kržišnik D, Lesar B (2021) Assessment of wooden foundation piles after 125 years of service. Forests 12(2):143

Kamath A, Kumar GSR, K S, Ravenshorst G (2025) Mechanical strength characterization of recovered Azobé timber boards for reuse. Case Stud Constr Mater 22:e04228

Klaassen RK (2008) Bacterial decay in wooden foundation piles—Patterns and causes: a study of historical pile foundations in the Netherlands. Int Biodeterior Biodegrad 61(1):45–60

Klaassen RKWM, Creemers JGM (2020) Assessment report: State of the wooden construction, fresh water marina, Akkrum [Report No. 2020-RK-JC-SHR]. SHR. Retrieved from https://www.shr.nl/app/uploads/2024/03/2020-rk-jc-shr-report-inspection-timbers-used-in-fresh-water-marina-akkrum.pdf

Lechner T, Nowak T, Kliger R (2014) In situ assessment of the timber floor structure of the Skansen Lejonet fortification, Sweden. Constr Build Mater 58:85–93

Llana DF, Íñiguez-González G, Plos M, Turk G (2023) Grading of recovered Norway Spruce (Picea abies) timber for structural purposes. Constr Build Mater 398:132440

Llana DF, Ridley-Ellis D, Turk G, Íñiguez-González G (2024) A proposed standardization framework for recovered timber strength grading. Presented at III congreso Ibero-Latinoamericano MAD de La Madera En La construcción (CIMAD 24). Libro de Actas de Resúmenes Extendidos, Madrid

Mirra M, Pagella G, Lee M, Gard W, Ravenshorst G, van de Kuilen JW (2024) Characterisation of bacterial decay effects on wooden foundation piles across various historical periods. Constr Build Mater 421:135670

NEN-EN, March (2005) NEN-EN 1997-1:2005 (Dutch Design Code). Eurocode 7: Geotechnisch ontwerp - Deel 1: Algemene regels (Eurocode 7 - Geotechnical design, Part 1: General rules)

NEN 5493 (2010) Quality requirements for hardwoods in civil engineering works and other structural applications. NEN, Delft

Nowak TP, Jasieńko J, Hamrol-Bielecka K (2016) In situ assessment of structural timber using the resistance drilling method–evaluation of usefulness. Constr Build Mater 102:403–415

Nowak T, Karolak A, Sobótka M, Wyjadłowski M (2019) Assessment of the condition of wharf timber sheet wall material by means of selected non-destructive methods. Materials 12(9):1532

Pagella G, Ravenshorst G, Mirra M, Gard W, van de Kuilen JW (2024) Innovative application of micro-drilling for the assessment of decay and remaining mechanical properties of historic wooden foundation piles in Amsterdam. Dev Built Environ 19:100514

Ravenshorst G, Gard W, van de Kuilen JW (2020) Influence of slope of grain on the mechanical properties of tropical hardwoods and the consequences for grading. Eur J Wood Prod 78:915–921

Van de Kuilen JW (2007) Service life modelling of timber structures. Mater Struct 40(1):151–161

Van de Kuilen JWG, Van Der Linden MLR (1999) Reliability based design of timber sheet pile walls. NZ Timber Des J 11(1):11–16

Van de Kuilen JGW, Blaß HJ (2005) Mechanical properties of Azobé (Lophira alata). Holz Roh- Werkst 63:1–10

Volume graphics (2022) (https://www.volumegraphics.com/en/products/myvgl.html)

Wesselink A, Ravenshorst GJP (2008) Application and quality requirements for (tropical) hardwoods. In: Conference COST E, vol 53, pp 29–30

Wood Handbook, Edition C (2010) Forest Products Laboratory