Vegetated Riprap

1) Overview

Description	ecological appreciation of loose riprap made of armour stones, including filter if necessary, through plants (optionally willow log branch cuttings, living fascines, hedge/brush layer) **desired vegetation:** sectional area by area integration (*according to the natural zoning*) of indigenous and site-adapted woody plants (*trees and/or shrubs – according to plant species and maintenance objectives*) into riprap, serving as stepping stone biotope for further species (plants/animals)
Bank protection	bank protection is ensured through riprap – dimensioned according to GBB[1)] – and filter if necessary, regardless of plants; planting does not provide any bank protection, additional local increase of the bank protection in the course of the continuous development of installed plants however is possible *(esp. of the roots*) applicable at bank sections already protected with riprap (subsequent vegetation) or at bank sections that require protection (vegetation during riprap installation) and feature a slope inclination of 1:2 or lower
Ecological potential *in comparison with riprap*	**support/development of stepping stone biotopes** - increase of structural and species diversity in the riparian zone - increase of the colonization potential for site-adapted animals (esp. birds), avoiding maintenance-pruning enables growth into aquatic zone with age → creation of fish refuge - creation of structures to enhance the network between aquatic and terrestrial habitats
Advantages/ Disadvantages	**advantages** - living materials, which can sometimes be cut in-situ - bank stability is ensured at all times (*after the excavation of plant trenches these must be refilled directly after plantation and covered with armour stones*) **disadvantages** - obtaining living material only during dormant season; tree nursery material should be of native origin, possibly limited availability - limited installation period (*weather, dormant season*) - high and dense vegetation may influence discharge (maintenance)

2) Components and installation	
Components **Plant elements**	**shoot-forming wood parts and/or woody plants** native and habitat-adapted woody plants of softwood and hardwood riparian forests *(mixture of male and female willow species; tree nursery material only with certificate of origin)*
Softwood riparian forest	**cuttings** (cf. Appendix 1a) ∅: 5 - 8 cm (*preferably wood parts of straight growth, primarily indigenous and site-adapted shrub willows and/or willow trees*) L: 35 - 80 cm **log branch cuttings** ∅: 5 - 15 cm (*see cuttings*) L: 100 - 250 cm **living fascines** (cf. Appendix 1b) ∅ branch material: 2 - 5 cm (*at least 70% of living branches, i.e. shoot-forming branches, primarily indigenous and site-adapted shrub willows and/or willow trees (limbs with lateral branches)*[13]) ∅ bundle of fascines: 45 - 55 cm L branch material: up to 500 cm **brush layers** Ø branch material: 2 - 4 cm (*primarily indigenous and habitat-adapted shrub willows and/or willow trees (highly branched limbs)*[13]) L branch material: 70 - 100 cm Willow trees: white willow (*Salix alba*), crack willow (*Salix x rubens*) Shrub willows: purple willow (*Salix purpurea*), almond willow (*Salix triandra*), common osier (*Salix viminalis*)
Hardwood riparian forest	**hedge layers** spillover-resistant saplings which form roots (*bare-rooted, twice transplanted seedling*) L: 60 - 100 cm Hardwood riparian forest species[8] (*3 plants/m*) depending on the flood tolerance: - with high flood tolerance[12]: bird cherry (*Prunus padus*), guelder-rose (*Viburnum opulus*), European spindle (*Euonymus europaea*), common hawthorn (*Crataegus monogyna*), common dogwood (*Cornus sanguinea*), - with low flood tolerance[9)10)12]: European ash (*Fraxinus excelsior*), common hazel (*Corylus avellana*), field maple (*Acer campestre*)

Components *(continued)* **Securing material**	**bracing wire** (*for the purpose of bundling the branches in living fascines*) diameter: 0.3 cm, annealed (*one bond per running meter*) **stakes** (*for the purpose of staking fascines and brush layers*) shoot-forming (*indigenous and habitat-adapted willows, additional root formation and denser vegetation*) non shoot-forming log woods $\varnothing_{stake}$: 6 - 8 cm L_{stake}: approx. 100 - 120 cm (*depending on the diameter of the fascine*)
Cutting and installation period	**cutting of living field-grown wood parts** dormancy period (= *period between shedding of leaves and budding; respect nature conservation regulations of BNatSchG [Federal Nature Conservation Act] when cutting branches of wild willows*) **obtaining living wood parts from tree nurseries** no time constraints **installation of shoot-forming wood parts (cuttings, log branch cuttings, brush layers)**[11)13)] *(during winter dormancy, on frost-free days with unfrozen ground)* Ideally: March/April *(immediate root formation after installation)*; depending on location and weather, installation is also possible until May **installation of bare rooted woody plants (hedge layer)**[11)13)] in spring or autumn, hence in the beginning or at the end of dormancy period
Boundary conditions for installation	**distance to water level** planting above mean water level/normal water level pay attention to riparian and habitat-adapted bank zonation of species (*e.g. softwood and hardwood riparian forest zone*) **slope inclination** ≤1:2 **lighting** sun or partial shade
Installation instructions	**excavation of planting trenches or planting holes** (cf. Appendix 2) excavation of trenches in the direction of the slope dip down to in-situ soil; if necessary, pre-drill planting holes down to in-situ soil **installation** (cf. Appendix 2) ***log branch cuttings and cuttings:*** *(zone: softwood riparian forest)* sharpen lower basal ends, drive in planting holes at a distance of 50 cm (*borehole must guarantee comprehensive soil contact of planting elements, otherwise, subsequent slurry with sand topsoil mixture*) or install in excavated planting trenches; saw off upper ends of log branch cuttings slightly inclined (*water runoff during rainfall*) ***living fascines:*** *(zone: softwood riparian forest)* installation in planting trenches (*basal ends of branches point in the direction of the slope toe*); fix fascine crosswise with stakes (cf. Appendix 1b)

Installation instructions *(continued)*	***brush layers:*** *(zone: softwood riparian forest)* install willow branches inclined to the direction of the flow so that only ¼ of their length protrudes beyond the slope surface (cf. Appendix 1a); place a soil layer of approx. 10 cm on branches ***hedge layers:*** *(zone: hardwood riparian forest)* Installation of saplings (*3 qty. per m*) inclined to the direction of the flow in planting trenches so that only ¼ of their length protrudes beyond the slope surface; place a soil layer of approx. 10 cm on saplings **water supply** log branch cuttings/cuttings, fascines, brush /hedge layers must have soil contact (use of slurry material if necessary) **distance of single planting/planting trenches** - distance of single planting: saplings approx. 30 cm; log branch cuttings, cuttings approx. 50 cm - distance of planting trenches: approx. 500 cm **securing** ***log branch cuttings/cuttings:*** after tight installation, no additional securing necessary ***living fascines:*** fixation of fascines crosswise with stakes (*one pair of stakes per m; drive in a stake each in front of and behind any coil of the fascine*) ***brush layers:*** no additional securing after replacement of armour stones ***hedge layers:*** see brush layers **procedure** (cf. Appendix 2) ***cuttings/log branch cuttings:*** 1) pre-drilling of a planting hole with a plant drill at a distance of 50 cm or excavation of planting trenches (*store armour stones and excavated material at the side*) 2) installation of a log branch cutting/cutting (*basal ends at the bottom*) and driving log branch cuttings slightly deeper into the ground 3) application of slurry of sand/topsoil mixture to the borehole or planting trench 4) saw-off upper end of log branch cuttings above the slope surface (*approx. 20-50 cm*) 5) reinstallation of excavated material and stones, stored at the side temporarily (*plant parts may not be damaged in this process*) ***living fascines*** 1) excavation of planting trenches (*store armour stones and excavated material at the side*) 2) installation of living fascines (*basal ends in direction of slope toe*) 3) fixation of fascines crosswise with stakes 4) covering fascines with excavated material (*approx. 3 cm*) stored at the side temporarily 5) reinstallation of armour stones laterally in the trenches *(carefully in order to prevent damage of plant parts*)

Installation instructions *(continued)*	***brush layers*** 1) excavation of planting trenches (*store armour stones and excavated material at the side*) 2) installation of a river gravel layer of approx. 10 cm in the trench (grading approx. 0/32) 3) installation of willow branches inclined to direction of flow on the bedding so that only ¼ of their length protrudes beyond the slope surface 4) place a soil layer of approx. 10cm on branches 5) reinstallation of armour stones at the sides of the trenches (*carefully, for the purpose of preventing damage of plant parts*) 6) pruning of branches to max. 10 cm length above the surface of riprap ***hedge layers*** 1) see brush layers 2) see brush layers 3) installation of saplings (*3 qty. per m*) inclined to direction of flow so that only ¼ of their length protrudes beyond the slope surface 4) installation of a soil layer of approx. 10cm on saplings 5) reinstallation of armour stones at the sides of the trenches (*carefully, for the purpose of preventing damage of plant parts*) **ensuring filter stability** through filter-stable revetment structure

3) Mode of action and load-carrying capacity

Mode of action	**protection against surface erosion induced by currents and waves**	
	right after installation	ensured through riprap
	in the long term	additional protection through continuous development of plants
	protection against sliding of the slope due to drawdown/excessive pore water pressure	
	right after installation	ensured through sufficient mass per unit area and a filter-stable structure of the riprap
	in the long term	additional protection through continuous development of plants, esp. through root formation in the area of planting trenches (*increase of shear strength of in-situ soil (cohesion due to roots), local soil nailing*)
	protection against hydrodynamic soil displacement due to drawdown/excessive pore water pressure	
	right after installation	ensured through sufficient mass per unit area and a filter-stable structure of the riprap
	in the long term	additional protection through continuous development of plants, esp. root formation in the area of planting trenches (*increase of shear strength of the in-situ soil (cohesion due to roots)*)
	general	
	shoots of living plant parts can favour ecologically valuable accumulation of dead wood and flotsam (*further structural elements*) on the slope, while causing an increase of the flow resistance at the same time	

Tolerance to hydraulic loading	**basis: present experiences gained at navigable waterways**[3) to 7)] **and watercourses without navigation** [15)] - drawdown: necessary mass per unit area of riprap (verification according to GBB[1)]) - wave height: depending on the stone class installed 1.0[*)] m[15)] for stone class $LMB_{5/40}$ (stone density: 2.6 t/m^3) 0.3 m *(measured load on the test stretch at the river Rhine, test section 1, until now)*[3) to 6)] - flow velocity close to the bank: depending on the stone size category installed 2.6[*)] m/s[15)] for stone class $LMB_{5/40}$ (stone density: 2.6 t/m^3) 1.0 m/s *(measured load on the test stretch at the river Rhine, test section 1, until now)*[3) to 6)] **) values apply for the stability of riprap – stone class $LMB_{5/40}$ and bigger (dimensioned according to GBB[1)]) on slope inclinations of 1:3 and smaller –, no sufficient experien-ces on the load-carrying capacity of the plants installed into the riprap yet*
Flooding tolerance	flooding tolerance differs depending on the species of woody plants installed flooding tolerance of softwood riparian species up to 80 days of flooding period per year (basket willow)[14)] up to 130 days (almond and purple willow), respectively 170 days (white willow)[10)12)14)] (*benchmark!*) flooding tolerance of hardwood riparian species up to 20 days of flooding period per year (hazel)[10),] up to 40 days (ash), respectively 90 days (spindle, hawthorn, viburnum, dogwoods)[10)12)] (*benchmark!*) flooding tolerance is additionally influenced by: flooding height, flow, age and growth height of trees and shrubs, flooding period (*during growing season or dormancy period*), plant vitality
4) Miscellaneous	
Maintenance	in general, no need for maintenance. exceptions are: - flood discharge is not sufficiently provided due to vegetation - traffic safety is affected negatively by vegetation (clearance for the purpose of visibility) - riprap is damaged the following applies thereafter: maintenance measures should be performed non-uniformly and in longer periods according to growth rates (willow trees and shrubby willows) and maintenance objectives maintenance between 1st October and end of February only (*according to BNatSchG*)
Examples at German Waterways	- test stretch at the river **Weser**[2)] near Stolzenau, km 241.550 - 242.300, right bank, (test section 12: riprap with willow cuttings/log branch cuttings; VF 14, 14a: riprap and row of alders), installation finished 1989 (*considering boundary conditions, very good development is observable until now*) - test stretch at the river **Rhine**[3) to 6)] near Lampertheim, km 440.600 - 441.600, right bank, (test section 1: log branch cuttings, willow fascines, brush/hedge layers), installation finished at the end of 2011 (*considering boundary conditions, very good development is observable until now*) - test stretch at the river **Saar** between Saarburg and Serrig, km 15.000, right bank, installation finished in 2008 (*considering boundary conditions, very good development is observable until now*)

Literature	[1] BAW (2011): Bundesanstalt für Wasserbau (Hrsg.), Grundlagen zur Bemessung von Böschungs- und Sohlensicherungen an Binnenwasserstraßen (GBB 2010), Eigenverlag, Karlsruhe 2011. [2] BAW, BfG (2008): Bundesanstalt für Wasserbau, Bundesanstalt für Gewässerkunde, Untersuchungen zu alternativen technisch-biologischen Ufersicherungen an Binnenwasserstraßen - Teil 2: Versuchsstrecke Stolzenau/Weser, Eigenverlag, Karlsruhe, Koblenz 2008. [3] BAW, BfG (2012): Einrichtung einer Versuchsstrecke mit technisch-biologischen Ufersicherungen, Rhein, km 440,600 bis km 441,600 (rechtes Ufer), Erster Zwischenbericht – Randbedingungen, Einbaudokumentation, Monitoring, 25.01.2012, available at http://ufersicherung.baw.de/de/index.html [4] BAW, BfG (2015): Einrichtung einer Versuchsstrecke mit technisch-biologischen Ufersicherungen, Rhein, km 440,600 bis 441,600 (rechtes Ufer), Teilbericht Standsicherheit und Unterhaltung, Monitoringergebnisse 11/2012 bis 10/2013, 30.03.2015, abrufbar unter http://ufersicherung.baw.de/de/index.html [5] BAW, BfG (2013): Einrichtung einer Versuchsstrecke mit technisch-biologischen Ufersicherungen, Rhein, km 440,600 bis km 441,600 (rechtes Ufer), Zweiter Zwischenbericht – Erste Monitoringergebnisse 2012, 20.06.2013, available at http://ufersicherung.baw.de/de/index.html [6] BAW, BfG, WSA MA (2016): Einrichtung einer Versuchsstrecke mit technisch-biologischen Ufersicherungen, Rhein, km 440,600 bis km 441,600 (rechtes Ufer), Fünfter Zwischenbericht – Monitoringergebnisse 11/2014 bis 10/2015, 08/2016, abrufbar unter http://ufersicherung.baw.de/de/index.html [7] BAW, BfG: Internetportal zur Thematik „Alternative technisch-biologische Ufersicherungen an Binnenwasserstraßen“, http://ufersicherung.baw.de/de/index.html [8] Bundesanstalt für Gewässerkunde (1965): Der biologische Wasserbau an den Bundeswasserstraßen. Verlag Eugen Ulmer. Stuttgart [9] Dister, E. (1983): Zur Hochwassertoleranz von Auwaldbäumen an lehmigen Standorten. – Verh. d. Ges. f. Ökologie, Bd. X: 325-335. [10] Dister, E. (1988): Ökologie der mitteleuropäischen Auenwälder. Wilhelm-Münker-Stiftung. Heft 19. S. 6-30. Siegen [11] Schiechtl, H. M. & R. Stern (2002): Naturnaher Wasserbau. Anleitung für ingenieurbiologische Bauweisen. Berlin. [12] Späth, V. (1988): Zur Hochwassertoleranz von Auenwaldbäumen, Natur und Landschaft 63, 1988, S. 312 bis 315 [13] Stowasser, A. (2011): Potenziale und Optimierungsmöglichkeiten bei der Auswahl und Anwendung ingenieurbiologischer Bauweisen im Wasserbau. Schriftenreihe Institut für Umweltplanung Leibniz Universität Hannover. Cuvillier Verlag Göttingen. [14] Westhus, W. (1986): Beobachtungen zur Überflutungstoleranz von Gehölzen und daraus abgeleitete Pflanzvorschläge. Hercynia N. F., Leipzig 23 (1986) 3, S. 346-353. [15] DWA (2016): Technisch-biologische Ufersicherungen an großen und schiffbaren Binnengewässern, Merkblatt DWA-M519, März 2016

5) Institutions / link	
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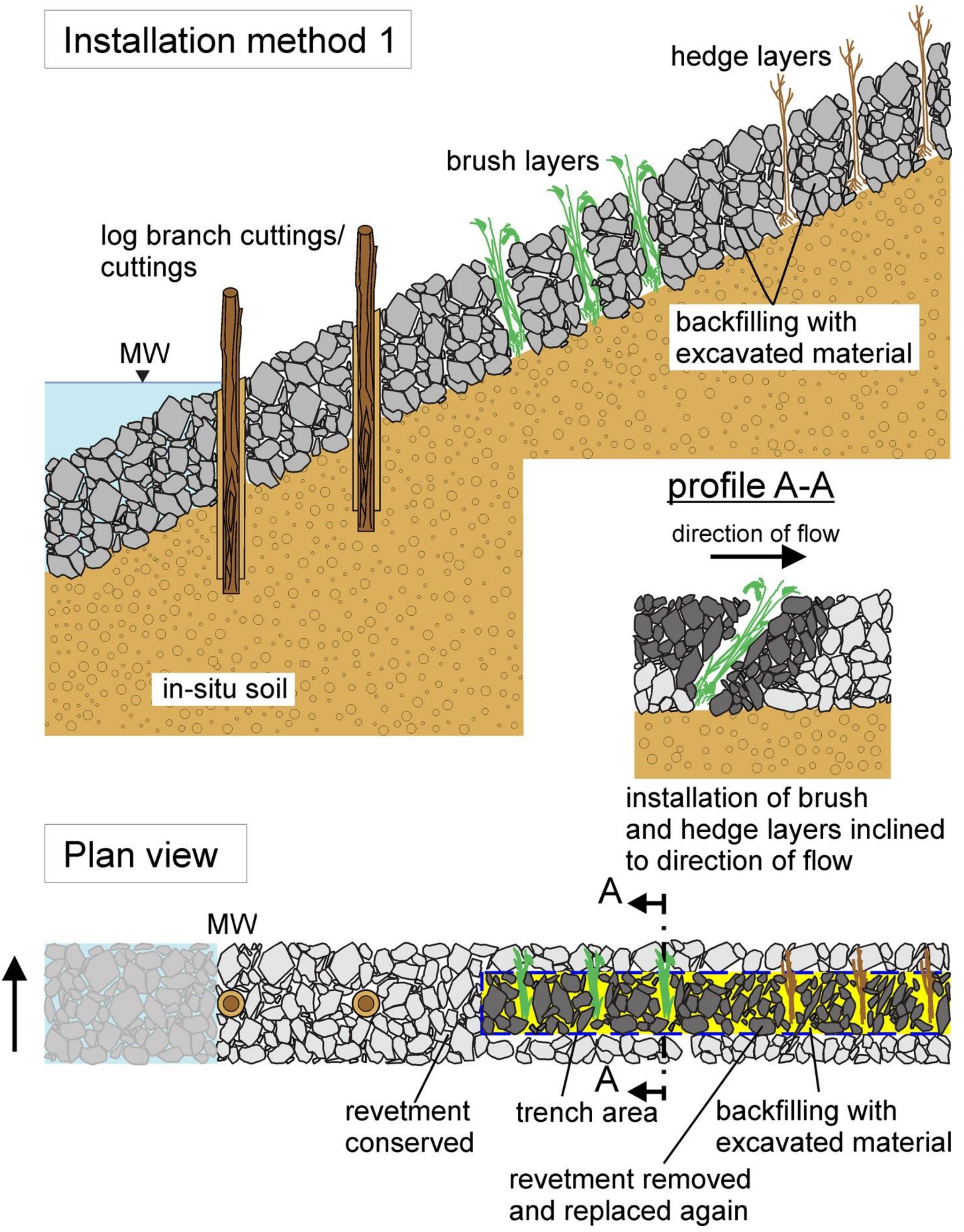
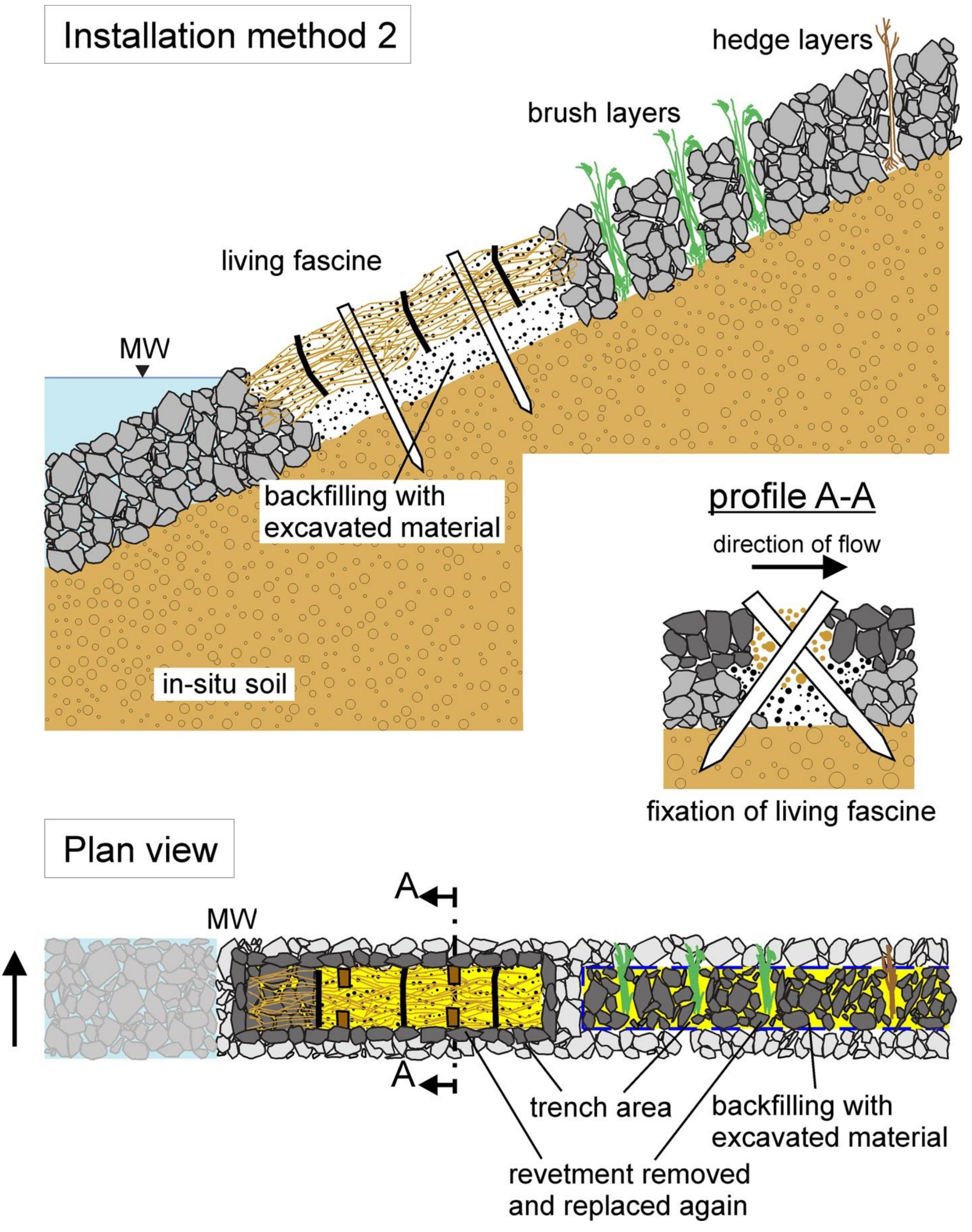
Link	For further information, please see: http://ufersicherung.baw.de/de

Appendix 1a **Schematic Figure**



Appendix 1b	**Schematic Figure**



Appendix 2 — Sample Photos

Source: Test Stretch Lampertheim/Rhine[3)4)5)6)] photos: BAW/BfG

(1) excavation of a planting trench in the loose armour stone revetment down to in-situ soil; Nov. 2011

(2) willow log branch cuttings installed into the planting trenches; Nov. 2011

(3) Willow fascines placed into the planting trenches and fixed with stakes; end of Nov. 2011

(4) bare-rooted saplings for the purpose of obtaining hedge layers; end of Nov. 2011

(5) installation of hedge layers in excavated planting trenches; end of Nov. 2011

(6) planting trench with one-year-old brush and hedge layers; Jan. 2013

(7) continuous development of willow log branch cuttings; April 2012

(8) shoots of willow fascines; end of April 2012

(9) continuous development of vegetated riprap; June 2012

(10) willow cuttings with shoots; June 2012

(11) willow log branch cutting with developed aerial roots (adventitious roots); Aug. 2013

(12) willow log branch cuttings 2 ½ years after installation; May 2014