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High Resolution Monitoring Of Retaining Wall Using Sensors

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ABSTRACT : Retaining walls are important structures to stabilize slopes in the vicinity of infrastructure objects likebuildings, highways and tunnel portals. In Austria, conventional monitoring of these walls is based onvisualinspectionandondeformationmeasurements ofafewdistinctivepointsonorwithinthestructure.However, these approaches leave large areas of retaining walls unobserved and thus relevant structuraldeficienciesmay bemissed.

We present a new approach consisting of remote surface-based measurements with mobile mappingsystemsandinternaldeformationmeasurementswithhighresolutiondistributedfiber optic sensors.

Fortheremotesensing,ameasurementplatformconsistingoftwolaserscanners,aninertialmeasurement unit (IMU), a differential GNSS sensor and several cameras was used. Whilst a standardcar with the attached multi sensor system platform travels with up to 100 km/h along the highway, dataiscontinuouslyrecordedwithhighfrequency.Asaresult,georeferencedhighresolutionpointcloudsofall retaining walls along the highway can be obtained. We further analyse the point clouds to derivesafetyrelevantparametersliketiltchangesof theretainingwalls.

Large retaining walls are often stabilized by fully or partly grouted anchors. We demonstrate that theutilizationgradeoftheseanchorscanbe measuredreliablywithdistributedfibreopticsensors(DFOS).From the DFOS measurements, the longitudinal strain and also bending properties of anchors can bedepicted

Keywords: Retaining walls, Fibre optic sensors, Mobile mapping systems, Laser scanning

I. INTRODUCTION

Retaining walls stabilize slopes in the vicinity of infrastructure objects like buildings, highways andtunnel portals. Failure of these structures can lead to death of highway users and the repair works cancause massive delays due to closures of highway lanes. In a recent incident a truck driver was killed ontheAustrianHighwayBrennerautobahn(A13)becauseofacollapseofaretainingwall[1].Consequently,retainingwallshavetobemonitoredduringtheirconstructionandtheirlifetimetoassessconstructionquality,to assurethesafety of peopleand toenablecondition-based maintenance.

Conventionalmonitoringapproachesarebasedondeformationmeasurementsofafewdistinctivepointson the surface of the structure and within the structure. Typically used sensors are total stations (TS)measuringangles(Hz,V)anddistances(D)toreflectivetargets(P),tiltsensors(T),boreholeinclinometers ,extensometers orelectricstraingauges (ESG),seeFigure1.

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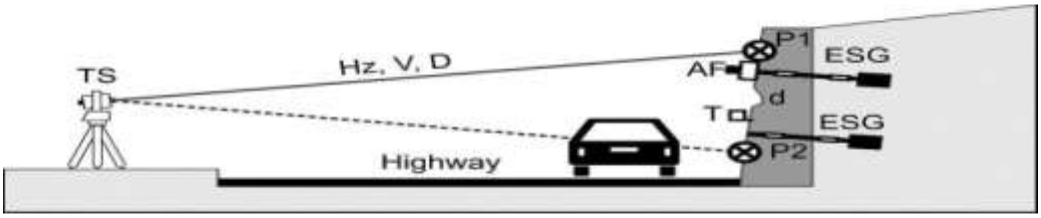


Figure1. Conventionalmonitoringsetupof ananchoredretainingwall

Figure 2 shows a retaining wall within the Austrian highway network. Reflective targets (P1 to P4) aremeasured in regular intervals with a total station. Two targets are always placed in the same verticalprofilein order to derivetiltchangesfromthe3D positionsof thetargets.

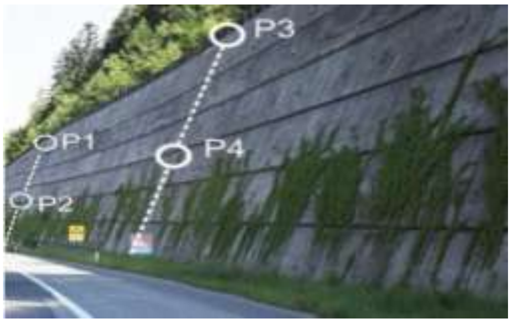


Figure2. Prismpositionsforthe geodetic monitoringofa rainingwall

Despite the immense effort of such a measurement installation, large areas of a structure remainunobservedandlocaldamagescannotbedetected.Moreover,inmanycases,itisfinanciallynotfeasibletomonitorallexistingobjects,e.g.severalthousandretainingwalls,withsuchameasurementprogram.

II. NEW MONITORING APPROACHES

In order to obtain a complete picture of the deformation behaviour of a single structure and to observeall structures within a network, more efficient monitoring methods are needed. As will be shown in thefollowing, mobile laser scanning is a valuable tool to analyse the surface behaviour of a structure indetail and distributed fibre optic sensors are well suited to assess the state of the internal supportingelements.

2.1 LaserScanningwithaMobileMappingSystem

Modern laser scanners are able to measure some million points per second. Conventionally, laserscanners are mounted on a static platform like a tripod or pillar. However, laser scanners can also beplaced on mobile platforms like planes, drones, cars or trains. Sometimes data from static and mobilelaser scanning are combined to deliver one large model. An example for this is given in [2], whereairborne laser scanning (ALS) is used to measure the surface of the terrain and static terrestrial laserscanning(TLS)isusedtomeasureunderground.Inordertomonitorretainingwallsalongroadsand railwaytracksmoreefficiently,weinvestigatedtheuse ofamobilemappingsystem(MMS),seeFigure3.

Figure 3. Mobile mappingsystemmountedonacar

The used MMS consists of a geodetic GNSS antenna with a receiver, an inertial measurement unit(IMU), two laser scanners, six cameras and an odometer. The entire measurement platform is mountedon a standard car. The position of the platform is calculated using differential GNSS and supported bytheIMUandodometerdata.TheorientationismainlydeterminedwiththeIMU.Thetwolaserscannerswork in profile mode and measure 1 million points per second each. Due to the high data acquisitionrate, high resolution point clouds are obtained even at high driving speeds. Finally, the camera imagesareusedtocolourthepointcloudandsupportthe classificationof thedetecteddamages.

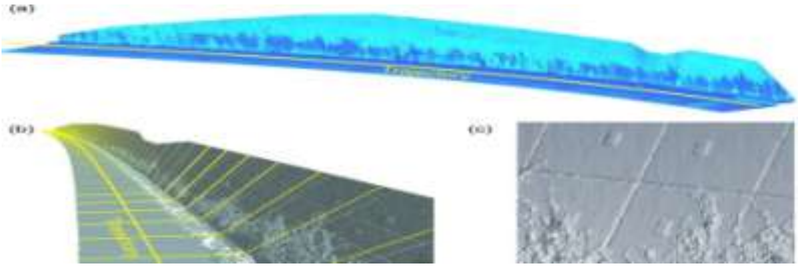


Figure 4. Point cloud (a) and TIN model (b) of the highway surface and retaining wall.

The cartrajectory and vertical profiles every 5 m are indicated as yellow lines. Detailed profiles (c) every 5 cmalongthetrajectory areused forfurtherprocessing.In the analysis [3], the point cloud (Figure 4a) is first converted into a surface model (Figure 4b), forinstanceintoatriangulatedirregularnetwork(TIN). Nextprofilesorthogonaltothetrajectoryofthecarareautomaticallygeneratedevery5cm(Figure 4c).Theindividualprofilesareevaluatedautomatically usingrobustestimationmethodstocalculate thetilt,derivedfroma fittedrobustregressionline,oftheretaining wall. In order to check the precision of the process, data of different walls were recorded multiple times at different driving speeds (60 km/h, 80 km/h, 100 km/h). A statistical analysis showed that the inclinations, depending on the type of retaining wall, can be determined with a standard deviation between ±0.007° (gravity wall with smooth concrete surface) and ±0.074 ° (dissolved anchored wall) [4].

By the robust tilt determination outliers are identified which may have multiple reasons. Outliers are categorized as significant deviations from the fitted regression line. Deviations are for instance caused by measurement errors but also by vegetation on the surface, construction elements on the wall or pop outs. An intelligent analysis of these outliers aims to identify and classify the outliers. We automatically group the outliers of different profiles and classify them. The recorded camera images are an essential data source for a reliably classification.

Figure 5-left depicts a typical result of the analysis of the mobile mapping data of a 40 years old wall. Displayed are grouped and classified outliers. Group (a) belongs to vegetation, group (b) are the horizontal joints of the wall and group (c) are the concrete protections of the anchor heads. Remarkable is group (d) which is a potential deficiency of the wall. In order to verify this assumption the recorded images are used. Figure 5-right shows that the outlier group (d) is in fact a pop out where concrete has fallen off the wall. Even the steel grid of the reinforced concrete is visible in the images. It has to be noted that this retaining wall is already monitored with conventional geodetic methods. Although the prism positions P1 and P2 may be measured with high accuracy, the damaged area in between the prisms remains undetected but can be found reliably using the mobile mapping data.

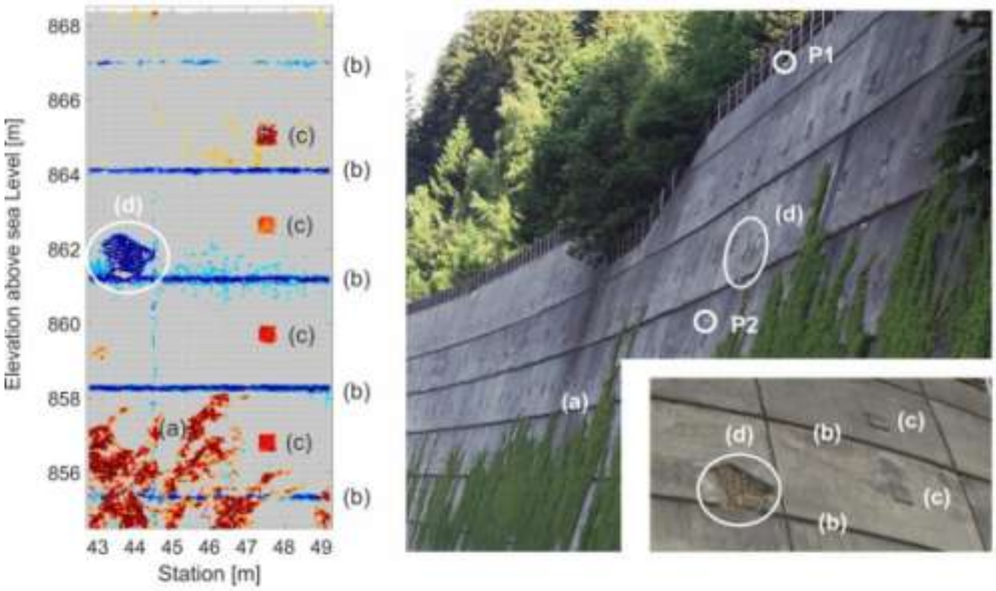


Figure 5. Automatically detected significant deviations from the linear regression lines (left), imagesof the retainingwallwithprismpositonsP1 andP2andlocaldamaged(right)

2.2 DistributedFibreOpticSensing

Similar to surface based measurements, internal measurements shall deliver reliable information andshouldbeabletodetectlocaldamageslikecracks.However,conventionalelectricsensorsusuallyhavelimitationsbecauseeitherthereisagapbetweenindividualsensingelementswheredamagesarenottransferred to the sensors or the connected sensors have such a long gauge length (e.g. in case of rodextensometers) thatalocaleffectisaveraged overalargedistanceandnotclearly visibleanymore.

Distributed fibre optic sensors (DFOS) overcome these drawbacks as the fibre itself acts as the sensorandtherefore,measurementsalongtheentiresensingcablearefeasible.Agoodoverviewofthecurrentstatus of various types of DFOS systems for applications in civil engineering is given in [5]. DFOS arealready used for a long time to detect leakages of pipelines or water dams. Leakages cause localtemperature anomalies, which can be detected for instance by Raman backscattering. Strain monitoringover longdistances isusually performedusingBrillouin scatteringtechniques [6].

Here, we focus on high resolution distributed fibre optic sensing based on Rayleigh backscattering,which enables measurements over short distances of e.g. 70 m with a measurement precision of someµm/manda spatialresolutionofabout10millimetre.Therefore,upto7000measurementpointscanberealized along one single sensing cable. Comparable measurements with conventional, geotechnicalsensors(e.g.electricstraingauges)arenot practicalduetotheirhighinstallationeffortaswellascablingissues.Nevertheless,ithastobeconsideredthatmanymanufacturesoffibreopticsensorsdonotspecifyindividual calibration parameters and refer to literature values instead, which might result in errors upto10%ormore.For thatreason,anindividualcalibrationofthe fibreoptic systemisessentialtoavoidsystematicerrorsandtoachievethespecifiedmeasurementprecisionwithintheharsh fieldenvironment.For details aboutsensorcalibration and testing,see[7]or [8].

Within the last years, we developed reliable methods to monitor geotechnical structural elements likepiles and anchors during load tests and in the long term [7], [9], [10], [11]. One of the retaining walls(Figure7-left) was recently(July 2018) equippedwhichafibreopticinstrumentedanchor.

Figure 6. Slope stabilization using ground anchors for retaining walls at highway (left) and at a refinery(right)
Figure 7. Schematic representation of single borehole multiple anchors with two sensing fibres alongthetendons of each individualanchorand twofibreloopsin thegroutmaterial

Measurements of this anchor are currently ongoing and the data analysis is in progress. We thereforereportinthisarticleaboutpull-outtestsofsingleboreholemultiplestrandanchors(SBMA),whichwereinstalled in 2016 for the slope stabilization of a refinery (Figure 7-right). To assess the behaviour of theanchorsunderload,weinstalledtwosensingfibresalongthetendonsofeachindividualanchorandtwofibreloopsinthegroutmaterial,asshowninFigure8.Duetothisredundantarrangement,measurementswouldhavebeen feasible,even ifonefibrehad broken.

Duringtheloadtestscontinuousfibreopticmeasurementswereperformedwhilsttheloadwasstepwiseincreased. As an example, the strain profiles along the anchor tendons and the grout material at threeloadsteps900kN,1500kNand2100kNaredisplayedinFigure9.Thetendonsshowanalmostuniform strain distribution along the free length of the anchor. Afterwards, the applied load is transferred fromtheanchortothesoilinthefixedlength(L_{fixed})andtherefore,thestrainvaluesdecreasewithincreasingdepth. Thereby, the area of the fixed length that is utilized for the load transfer increases with higherloads, which demonstrates a progressive failure of the tendon/grout interface. This behaviour can alsobe depicted in the grout material along the fixed length of each individual anchor, in which cracks(representedby local strain peaks) become visible. As it can also be seen, the last 0.5 m of the fixedlength of the middle anchor (hatched area in Figure 9) is not influenced at the maximum testing load of2100 kN. This might be an indicator that the final bearing capacity of this individual anchor is notachieved and thus the entire anchor works well at its designed lower operating load. More informationontheinstallation anddataevaluationofthesetests canbefoundin [7].

In a different layout, slopes and construction pits are stabilized using fully grouted steel anchorscombinedwithshotcretelayersatthesurface.Contrarytotheabovementionedstrandanchors,theseso-called “soil nailing systems” do not have a free separated anchor length. In order to assess the bendingbehaviourofsuchananchoringsystems,we

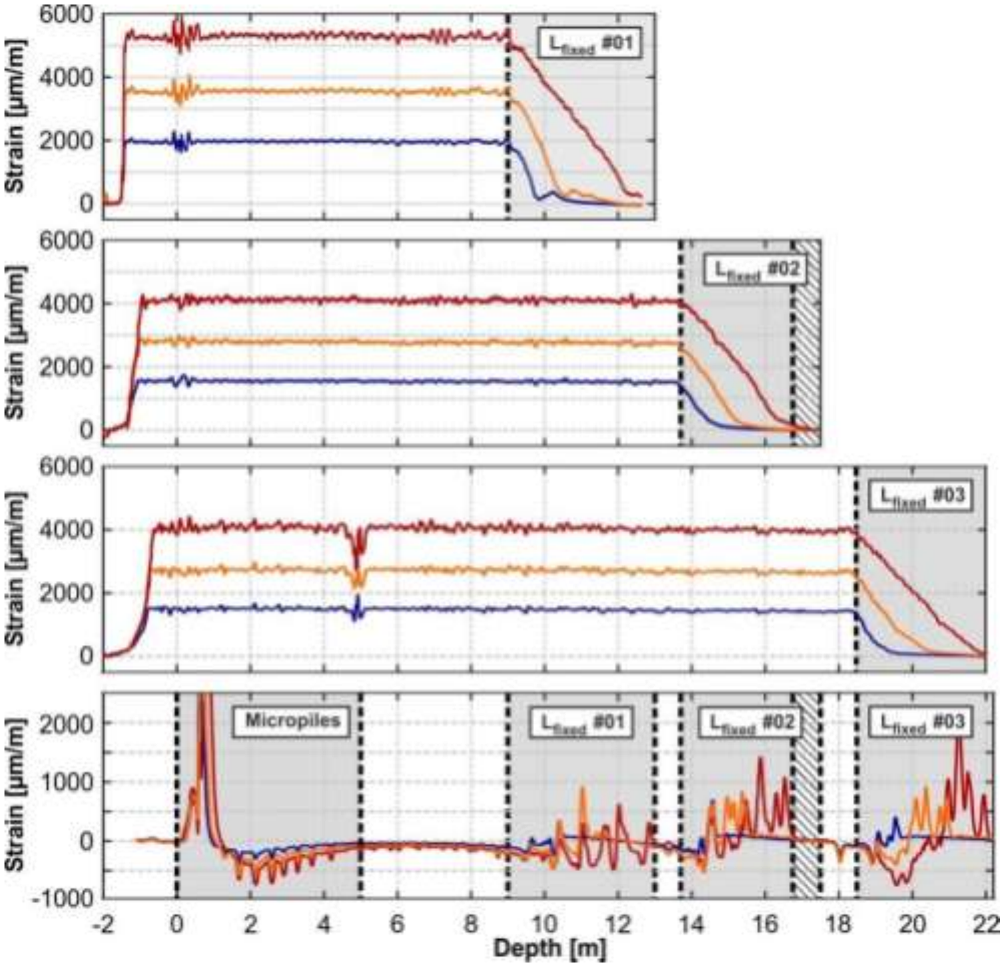


Figure 8. Measured strain profiles at load steps of 900, 1500 and 2100 kN along the anchor tendons oftheshort(#01), middle(#02)and long(#03)SBMA anchor and thegroutmaterial

glueafibreopticstrainsensingcableingroovesonthetopandbottomofthesteelnails(Figure10-right).Thefeasibilityofthisapproachwasverifiedinlaboratoryinvestigations,wherecontrolledbendingwasappliedtoinstrumentednails.Thetruedeformedshapeofthe nails was determined with laser and image based methods and compared to the derived shape fromthefibreopticmeasurements, see[10]and [11].

Three instrumented soil nails were also placed into a slope of a road construction site. For temperaturecompensation an additional temperature sensing cable was also installed along every nail. Continuousmonitoringoverseveralweeksstartedrightafterconstruction.Additionally,apull-outtestofoneofthenails (nail #03) was performed after the monitoring campaign. Detailed information and results of thecontinuousmonitoring as wellas thepull-outtestcan befoundin [10].

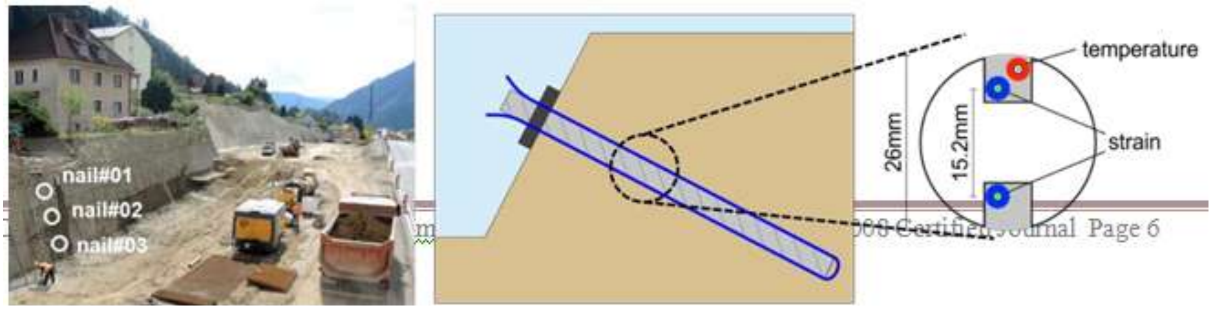


Figure 9. Fibre optic equipped soil nails at a construction site with three sensing nails (left) and their cablelayout(right)

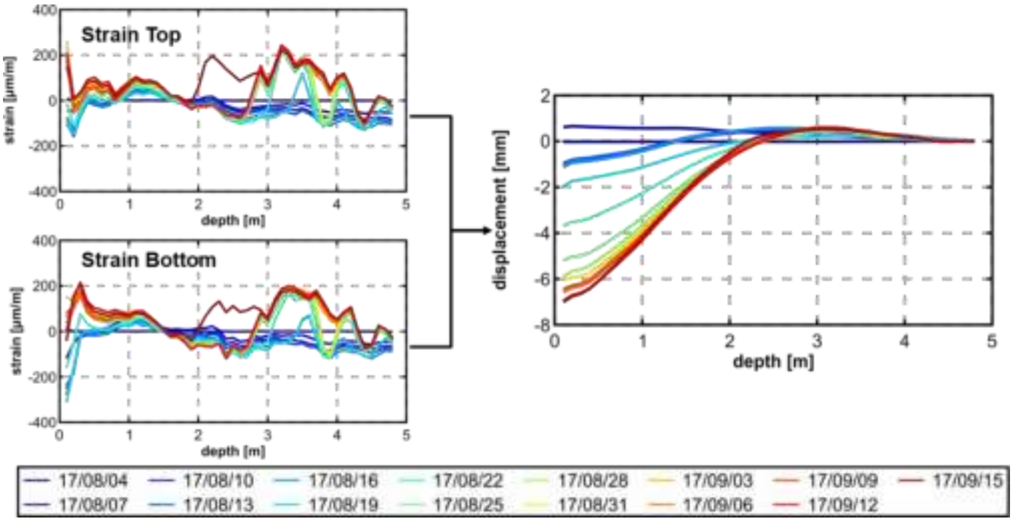
As already mentioned, strain changes were measured along the top and bottom of each nail. Knowingthe lateral distance between the top and bottom fibre, curvature changes can be derived from the straindifferences.Assumingthatthepositionofthenailenddoesnotchange,theshapechangecanbederivedby double integration. Figure 11 shows the strain values of the top and bottom fibre of nail #1 and thecalculatedverticaldisplacements.

The bending of the nail resulted in a vertical displacement of about 7 mm at the front end of the nailwithintheobservationperiodofmorethanonemonth.Theconstructionsequenceofthewallissupposedto be the reason of this bending. Nail #1 was installed when the level of the road lane was much higher.Following,thesoilwas removeduntilitreached thelevelshown in Figure10-left.

Figure10. Strainprofilesalong thetopandbottomof nail#1and deriveddisplacementcurve.

III. CONCLUSION

In this paper, we presented new, more efficient approaches to detect changes of the surface of



largestructures and to assess the internal behaviour of structural elements using laser scan, image anddistributed fibre optic data. The individual measurement points of the presented surface measurementmethodsmaynothavethesameprecision asconventionalsingle-pointmeasurementstoprismsbuthavethe big advantage that the entire structure is monitored and local damages can also be detected. Weshowed that point clouds from a moveable laser scanner can be used to automatically derive relevantdeformationparametersliketiltchangesortodetectstructuraldegradationeffectslikepopouts.Inordertoassessthestructuralbehaviourinternally,distributedfibreopticmeasurementmethodsareparticularlypromisingbecausethousandsofmeasurementpointscanberealizedwithasinglecableandmeasurements with high accuracy are possible. We demonstrated that the internal deformations and theutilization grade of anchors of slope stabilizations can be reliably measured with distributed fibre opticsensors.If anewretainingwallis beingbuilt,DFOSsensorscouldalsobeembeddedalongthewall.

Alldifferentmonitoringmethodstogetherdeliveramorecompletepictureofthedeformationbehaviourof a large structure and thus, a modern monitoring setup of retaining walls can look like depicted inFigure12.

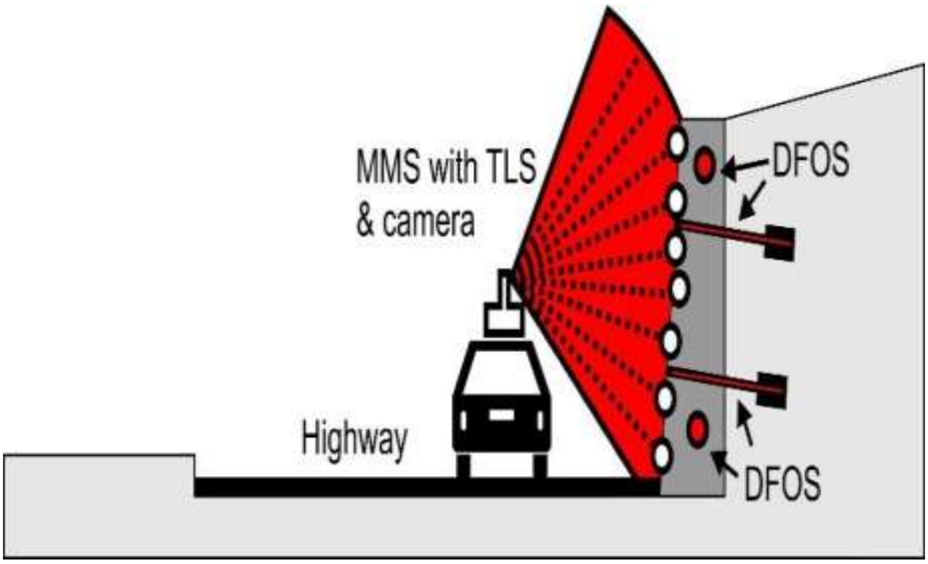


Figure11. Exampleofamodernmonitoringsetup ofananchoredretainingwall

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