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Submit only ONE copy of this form **for each PI/PD and co-PI/PD** identified on the proposal. The form(s) should be attached to the original proposal as specified in GPG Section II.B. Submission of this information is voluntary and is not a precondition of award. This information will not be disclosed to external peer reviewers. ***DO NOT INCLUDE THIS FORM WITH ANY OF THE OTHER COPIES OF YOUR PROPOSAL AS THIS MAY COMPROMISE THE CONFIDENTIALITY OF THE INFORMATION.***

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**Gender:** ☒ Male ☐ Female

**Ethnicity:** (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

**Race:**
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- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

**Disability Status:**
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

**Citizenship:** (Choose one) ☐ U.S. Citizen ☐ Permanent Resident ☒ Other non-U.S. Citizen

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**American Indian or Alaska Native.** A person having origins in any of the original peoples of North and South America (including Central America), and who maintains tribal affiliation or community attachment.
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### SUGGESTED REVIEWERS:
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PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 09-1

NSF 09-524 03/27/09

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Off. of Research & Proj. Admin.
4 New South Building
Princeton, NJ 08544-0036

AWARDEE ORGANIZATION CODE (IF KNOWN)

0026278000

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☐ SMALL BUSINESS ☐ MINORITY BUSINESS
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☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **NEESR Payload - Fiber Optic Method for Buried Pipelines Health Assessment after Earthquaker-Induced Ground Movement**

| REQUESTED AMOUNT | PROPOSED DURATION (1-60 MONTHS) | REQUESTED STARTING DATE | SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE |
|---|---|---|---|
| $ 99,968 | 24 months | 02/01/10 | |

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☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
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PI/PD DEPARTMENT

Civil and Environmental Engineering

PI/PD POSTAL ADDRESS

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| CO-PI/PD | | | | |
| CO-PI/PD | | | | |
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# CERTIFICATION PAGE

## Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the Authorized Organizational Representative or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), nondiscrimination, and flood hazard insurance (when applicable) as set forth in the NSF Proposal & Award Policies & Procedures Guide, Part I: the Grant Proposal Guide (GPG) (NSF 09-1). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

### Conflict of Interest Certification

In addition, if the applicant institution employs more than fifty persons, by electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.A; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

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By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Grant Proposal Guide.

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(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Grant Proposal Guide.

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The following certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

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The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

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Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:

(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

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| --- | --- | --- |
| NAME | | |

| TELEPHONE NUMBER | ELECTRONIC MAIL ADDRESS | FAX NUMBER |
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| | | |

* EAGER - EArly-concept Grants for Exploratory Research
** RAPID - Grants for Rapid Response Research

# NEESR Payload – Fiber Optic Method for Buried Pipelines Health Assessment after Earthquake-Induced Ground Movement

## Project summary


***Intellectual merit of the proposed activity***

Natural disasters, in particular earthquakes, can cause damage to pipelines which transport life and society sustaining supplies, such as water or hydrocarbons. Earthquake damage to pipelines can have disastrous humanitarian, social, economic, and ecologic consequences. Consequently, real-time, and automatic or on-demand assessment of damage to pipelines after the earthquake is essential for early emergency response, efficient preparation of rescue plans, and mitigation of the disastrous consequences. Assessment is particularly challenging for buried pipelines. A method for real-time, automatic or on-demand, assessment of health condition of buried pipelines after the earthquake will be developed in this Payload project. The method will be based on the use of distributed fiber-optic sensing technology and will be applicable to both concrete – segmented and steel – continuous pipelines. The focus will be on damage detection and localization generated by earthquake induced ground displacement. The proposed research will be accomplished through four tasks: (i) research and development of appropriate sensor topologies for different types of pipelines based on numerical modeling, (ii) development of novel sensors and installation procedures, (iii) validation testing, and (iv) data analysis. Beside the assessment of damage the method can be used for long-term structural health monitoring and operational monitoring, which will serve as an important input for life-time maintenance activities. The central part of the project, validation testing, will be performed at NEES Lifeline Experimental and Testing Facilities at Cornell University. This Payload project will be accommodated by NEESR award project CMMI-0724022, which also explores advanced techniques for damage detection of buried pipelines. Both projects will profit from the synergy – the same numerical models will be used, results obtained by different systems can be compared, and faculty from four universities will collaborate.

***Broader impacts resulting from the proposed activity***

The proposed method will help mitigate disastrous consequences of the earthquake-induced damage to pipelines, but it will also help life-time maintenance activities of pipelines through structural health monitoring and operational monitoring. This will have a direct broad impact to society through an increase in safety for the human population and goods, the containment of economical losses for industry and users, and the preservation of the environment. Broadened participation will be achieved through teamwork with other NEESR award partners. For example, research collaboration will be established with faculty and students of NEESR award partner Merrimack College, MA, which is a non-PhD-granting institution. Being engaged with both teaching and research, the PI will include the outcomes of the project in university courses at both the undergraduate level (structural analysis course) and graduate level (structural health monitoring course), and graduate students will be involved in undergraduate teaching activities. Results of the project will be disseminated to relevant industries, practitioners, and the broader public in the form of newsletters, website pages, papers published in scientific journals and professional magazines, documents, posters, and presentations via web-seminars (webinars). An association with the NEESR award will enhance the infrastructure for research and education by establishing collaborations between several US universities, stimulating development of novel methods and advanced technologies, stimulating dissemination of the next generation instrumentation, and operating shared NEES research infrastructure. The project necessitates research in several disciplines and consequently, a multi-disciplinary collaboration will be established and project will be presented in multi-disciplinary work-shops and conferences at the national and international level. The NEEScentral repository of research data will be used to realize broader outreach to research community, academic institutions, and public.

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For font size and page formatting specifications, see GPG section II.C.



*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

# NEESR Payload – Fiber Optic Method for Buried Pipelines Health Assessment after Earthquake-Induced Ground Movement

## 1. Project Team Table (Table 1)

| Participant/Affiliation | Expertise | Project Role |
|---|---|---|
| Branko Glisic<br>Assistant Professor of Civil and Environmental Eng.<br>Princeton University<br>P.I. | Structural health monitoring, fiber optic sensors and monitoring systems, damage detection and data analysis, structural analysis | Leadership in structural health monitoring using fiber optic technologies. Inspection of pipeline condition using distributed fiber optic sensors, including design of monitoring strategy, sensor instrumentation and data assessment and analysis. |
| Radoslaw L. Michalowski<br>Professor of CEE,<br>University of Michigan<br>P.I. of NEESR Award | Mechanics of granular media, soil-structure interaction, load on buried structures, math. modeling | P.I. of NEESR Award that will accommodate this Payload project. Coordination of test planning and execution at Cornell NEES site. |

## 2. Experimental Facilities Table (Table 2)

| Experimental Facility | Planned Schedule / Duration | Purpose |
|---|---|---|
| Large Displacement Facility – NEES Equipment Site at Cornell University | June 2010 and June 2011<br>Total duration of tests at Cornell NEES facility is two months | The central tests of Payload project, i.e. validation tests of proposed method, will be performed at Cornell NEES facility. |
| SHM Laboratory at Princeton University | Duration of tests at SHM Laboratory at Princeton is estimated to 4-6 months in period February 2010 – May 2011 | Preparative tests such as testing of monitoring equipment, sensor development and calibration, development of installation procedures, etc. will be performed in SHM Laboratory at Princeton University. |

More details about the facilities are given in section *Facilities, Equipment, and Other Resources*.

## 3. Functional Budget Table, Schedule of Major Tasks and Use of NEES Facility (Table 3)

| Project tasks and activities | Year 1* | | | | Year 2* | | | | Cost [US$] |
|---|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | |
| T 1: Development of sensor topologies | | | | | | | | | 15,000 |
| T 2: Develop. of sensors and install. proc. | | | | | | | | | 24,000 |
| T 3: Validation tests at NEES site | | | | | | | | | 39,000 |
| T 4: Data analysis | | | | | | | | | 17,000 |
| Educational and outreach activities | | | | | | | | | 3,000 |
| NSF reports / NEEScentral | | | | | | | | | 2,000 |

*Quarters indicates project year quarters, not calendar quarters; beginning is planned for February 2010.

## 4. Summary of Proposal Preparation Discussion with NEES Equipment Site Personnel

The PI was in contact with Cornell NEES site Operations Manager Mr. Joseph Chipalowsky in March 2009. The PI presented the layout of validation tests to be performed at Cornell NEES Site, including the list of equipment to be used, schematic drawings of installation and connections, and the project risk and mitigation plan. Mr. Chipalowsky encouraged the realization of the proposed tests, with a confirmation that the Cornell NEES site can accommodate the test. The same testing set-up as planned for NEESR award, and with no additional cost, can be used, provided that the proposed test layout is maintained and no further modifications of the set-up are requested. The PI of NEESR award, Professor Radoslaw L. Michalowski will coordinate the test planning and execution.

## 5. Vision

Pipelines are often exposed to natural hazards such as landslides and earthquakes, and to the third-party interferences, such as vandalism, obstruction or terrorist acts. These hazards can significantly change the original structural functioning of the pipeline, leading to damage, leakage, and failure with serious humanitarian, social, economic, and ecologic consequences. Furthermore, the operational conditions of the pipeline itself can induce additional wear or even damage.

For buried pipelines, earthquake represents one of the most severe natural hazards from many points of view. It can cause multiple damages in pipeline systems. Economic losses due to the physical damage of the pipelines, loss of transported (leaked) material, and the interruption of supply is de-facto high. But lack of supplies provided by pipeline, notably in the case of water, can have dramatic humanitarian consequences to the population, such as contamination and epidemic outbreaks, with potential long-term social consequences. Leakage from damaged oil pipelines can cause pollution with long-term ecological consequences.

Therefore, real-time assessment of the pipeline health condition after an earthquake is of crucial importance. It may allow an early emergency response, efficient preparation of rescue plans, and help mitigate the destructive consequences.

A modern pipeline must be able to “generate” the information concerning the changes in its structural health condition and potential damage induced by earthquake, and to communicate this information to responsible operators and decision makers, in-time – automatically or on-demand, and reliably. To achieve this, a modern pipeline should be equipped with a “nervous system”, a “brain” and “voice lines”, i.e. with a monitoring system which is continuously in operation and able to sense structural conditions at virtually every point of the pipeline and in the surrounding soil. The system should be able to automatically detect, recognize, localize, and report the damage. The current expertise and field experience in the domains of structural health monitoring, fiber-optic sensing technologies, and data analysis at Princeton University, sustains the confidence that the design and realization of such a monitoring system is feasible.

## 6. Literature Review

***Damage to buried pipelines caused by seismic events, and existing inspection technologies***

NEESR award project CMMI-0724022, entitled “NEESR SG – Damage Detection and Health Monitoring of Buried Pipelines after Earthquake-Induced Ground Movement”, will accommodate this Payload project, if granted. Literature reviews on damage to buried pipelines as well as on the existing inspection technologies and on the novel technologies with great potential for applications in this domain, are in an exhaustive manner presented in the NEESR award project description document; therefore they are not fully repeated in this document, but only a brief synopsis is given.

Earthquake-induced damage for pipelines is in general classified as being generated by transient ground deformation (TGD) or permanent ground deformation (PGD), (Torpak and Taskin 2007). Historical records are concordant with a widely accepted opinion that the most serious cases of earthquake-induced damage to pipelines were generated by strong ground motion or site failure, i.e. by permanent ground deformation (PGD) (e.g. Pei et al. 2005), and that is why this Payload project and the NEESR award project focus on the damage generated by PGD. The distribution of PGD depends on several factors, such as intensity and duration of earthquakes, site grade, soil type, type of pipe, and the location of the water table (e.g. O'Rourke 1998), and diverse correlation for pipe damage rate depending on types of pipe and PGD have been proposed by various researchers (e.g. Pei et al. 2005, O'Rourke 1998, just to name a few).

A pipeline subjected to PGD is, in a given cross-section, mainly exposed to bending and shear, while integrated normal stress may result in overall tensile or compressive force depending on pipeline orientation with respect to fault plane. Several numerical models have been developed in order to assess the vulnerability of pipeline to earthquake loads and describe pipe-soil interaction (e.g. O'Rourke and Liu 1999, Allouche and Bowman 2006, Karamitros et al. 2007) taking into account different deformation modes and pipe structure (continuous or segmented). Detailed Finite Element Analysis (FEA) have been performed as well (Liu and O'Rourke 1997, Yimsiri et al. 2004), and will be performed in the course of the NEESR award project. Both simplified models and FEA will be used in this Payload project to analyze the results of monitoring.

Existing technologies employed for inspection of buried pipelines are mainly based on the use of devices that can be inserted in the interior of the pipe. These devices may contain various types of sensors, typically depending on the type of the pipe. The most common device used for inspection of metallic pipelines is the so-called pig (Liu 2003). It is a small package containing mostly two types of sensing transducers: remote field eddy current and ultrasonic transducers (e.g. Kobayashi 1999). Electrical coils on the pig generate eddy currents in the pipe walls (Najafi and Gokhale 2004), while the damage, such as corrosion or cracking, alters their flow through the pipe walls and is detected as a variation in the remote magnetic field. Ultrasonic transducers are used to assess distribution of thickness of the pipe walls along the pipe length, and to detect any damage due to corrosion as a change in the wall thickness. For concrete pipelines, cameras are either placed on a robot and moved through the pipeline using the robotic system (Sinha and Fieguth 2006), or they are simply installed at a manhole access point. Besides the use of a camera, ultrasonic systems can also be used when the internal area of a pipeline is accessible (Wirahadikusumah et al. 1998).

The acoustic and ultrasonic transducers can also be installed on the surface of the pipe. Piezoelectric elements can be mounted on the walls of the pipe and they can introduce guided elastic waves, called Lamb waves, into the walls of pipe. The propagation properties of waves, such as attenuation, velocity or reflections can be correlated with the health condition of the pipe walls. In metallic pipes the Lamb waves can be directed (Rose 1999, Towfighi et al. 2002) and they propagate over distances of up to 1 km. However, Lamb waves are of limited application for concrete pipelines due to their high attenuation (Mandayam et al. 2001). Remote sensing technologies for monitoring concrete pipelines deployed above the surface, are infrared thermography systems (ITS) that capture thermal images of soil altered by leaks due to the rupture of pipe (Weil 1998), and ground penetrating radar (GPR) that captures reflections from boundaries of two different dielectrics and detects damage as alterations. Both technologies are challenged by reliable image interpretation.

Although several existing technologies are employed for assessment of pipeline health condition, none of them are fully suitable for the real-time automated operation. In general, they require manual operation and data analysis which adds subjectivity to the process. NEESR award project proposes a novel approach to the assessment of the pipeline health condition based on the self-detection capacity of cementitious materials, i.e. on the damage induced changes in their electrical properties (Lynch and Hou 2005) and acoustic properties (Yoon et al. 2000, Puri 2006). The wireless sensors with embedded algorithms will be developed in order to avoid complex data handling, transmission, and analysis. The use of wireless technologies was proven in field on above-ground structures (e.g. Lynch et al. 2006) and has a very promising potential for applications on buried structures.

***Distributed fiber optic technologies for pipelines health condition assessment***

<u>General overview</u>

There is a large variety of fiber-optic sensors (FOS) for structural health monitoring, developed by both academic and industrial institutions. Figure 1 classifies the long-term field proven fiber-optic strain and/or temperature sensing technologies according to the measurement principle (Glisic and Inaudi 2007).

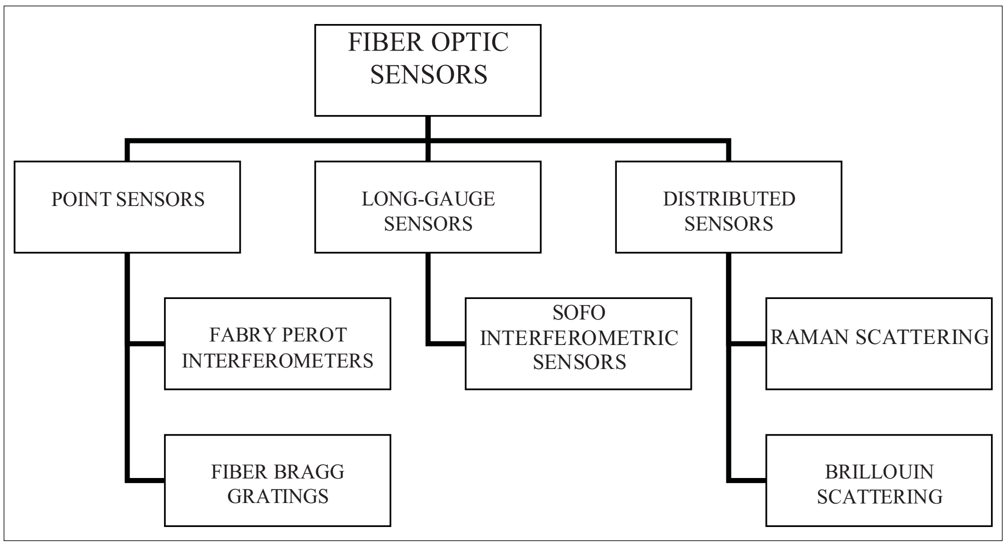


Figure 1: Classification of long-term field proven fiber-optic strain and/or temperature sensing technologies (Glisic and Inaudi 2007).

The greatest advantages of the fiber-optic sensors are intrinsically linked to the optical fiber, which is either simply a link between the sensor and the signal conditioner, or is the sensor itself. Glass, since it is an inert material very resistant to almost all chemicals even at elevated temperatures, is an ideal material for applications in harsh chemical environments. It is resistant to weathering effects and it is not subject to any corrosion, which is a great advantage for long-term reliable health monitoring of pipelines (Udd 2006). Various packaging especially designed for field applications made fiber optic sensors robust and safe to use even in very demanding environments (Udd 2006).

Since the light confined in the core of the optical fibers used for sensing purposes does not interact with any surrounding electromagnetic (EM) field, fiber-optic sensors are therefore intrinsically immune to any EM interference (EMI). The ability to measure over distances of several tens of kilometers without the need for any electrically active component is also an advantage inherited from the fiber-optic telecommunications industry. This is an important feature when monitoring large and remote structures, such as pipelines (Udd 2006).

Fiber-optic sensors offer a great variety of parameters that can be measured (e.g. strain, inclination, temperature, humidity, etc.), so that multiple parameters can be mixed on the same network (e.g. Li et al. 2004, Del Grosso et al. 2005). Compared with conventional electrical sensors, fiber-optic sensors offer new and unique sensing topologies, including in-line multiplexing and fully distributed sensing, offering novel monitoring opportunities. Finally, the tremendous developments in the optical telecommunications market have reduced considerably the cost and increased the performances of optical fibers and their associated optical components (Glisic and Inaudi 2007).

*Distributed fiber optic sensing technologies*

The method to be researched and developed in this project is based on the use of distributed strain and temperature monitoring system. Strain sensing is proposed, since the PGD actually strains the pipe, while temperature sensing is proposed since the damage of pipeline is often correlated with leakage that can be indirectly detected as a change of thermal parameters in the surrounding soil. Finally, the distributed technology is proposed taking into consideration particularly large lengths of the pipelines and the uncertainty of the location in which the damage can occur.

Distributed sensor (or sensing cable) can be represented by a single cable which is sensitive at every point along its length. Hence, one distributed sensor can replace thousands of discrete sensors. Moreover, it requires single connection cable to transmit the information to the reading unit, instead of a large number of connecting cables required in case of wired discrete sensors. Finally, distributed sensors are less difficult and more economic to install and operate. An illustrative comparison between pipelines equipped with distributed and discrete sensors is shown in Figure 2 (this schematic drawing does not refer to real case, e.g. redundancy is not included).

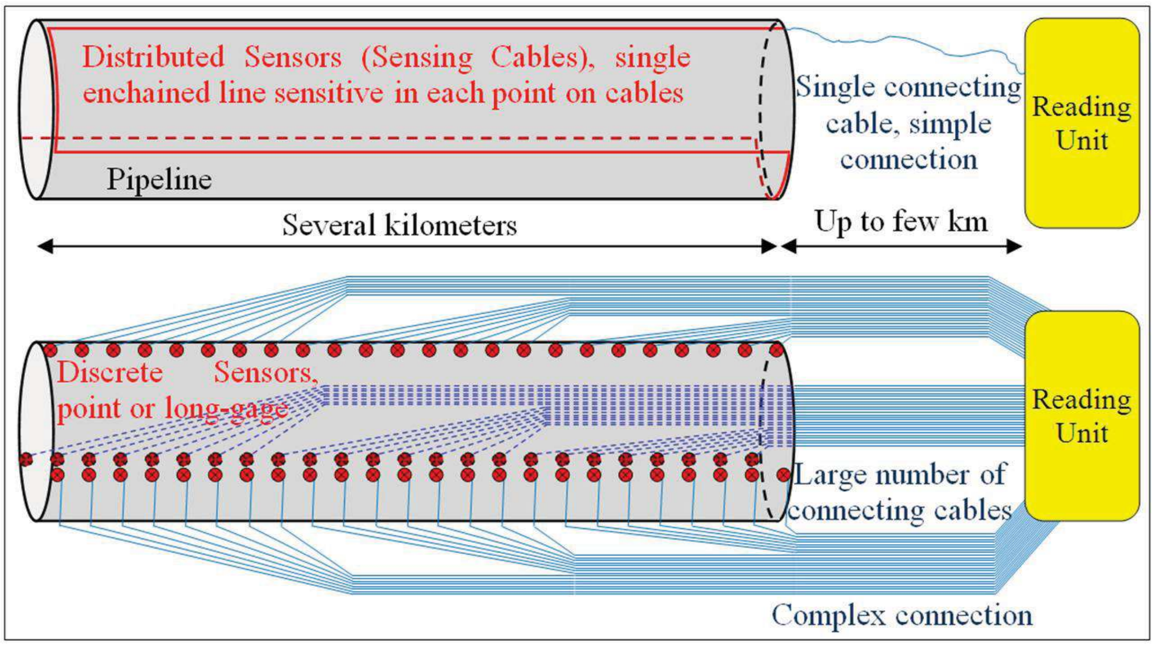


Figure 2: Distributed vs. discrete monitoring, schematic comparison (does not refer to real case).

There are three main principles for distributed sensing in the domain of FOS: Rayleigh scattering (e.g. Posey et al. 2000), Raman scattering (e.g. Kikuchi 1988) and Brillouin scattering (e.g. Karashima et al., 1990). Rayleigh scattering for strain monitoring is still under development. Raman scattering allows only temperature monitoring, thus more details are given on Brillouin scattering, which allows both strain and temperature monitoring.

Brillouin scattering occurs because of an interaction between the propagating optical signal and thermally excited acoustic waves in the gigahertz range present in the silica fiber, giving rise to frequency-shifted components (Karashima et al., 1990). It can be seen as the diffraction of light on a dynamic grating generated by an acoustic wave (an acoustic wave is actually a pressure wave that introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift, since the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly related to the density of the medium that is temperature and strain dependent. As a result, the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fiber.

Both spontaneous (Wait and Hartog 2001) and stimulated (Nikles et al., 1994, 1997) Brillouin scattering can be used for sensing purposes. The active stimulation of Brillouin scattering is achieved by using two optical light waves. In addition to the optical pulse, usually called the pump, a continuous wave (CW) optical signal, the so-called probe signal, is used to probe the Brillouin frequency profile of the fiber. The interaction leads to a larger scattering efficiency, resulting in an energy transfer from the pulse to the probe signal and an amplification of the probe signal. Monitoring system based on stimulated Brillouin scattering is less sensitive to cumulated optical losses that may be generated in sensing cable due to manufacturing and installation, and allows for monitoring of exceptionally large lengths (Thevenaz et al. 1999), e.g. in the case of strain monitoring, a single reading unit with two channels can operate measurement over lengths of 10 km, while in the case of temperature monitoring, the lengths of 50 km can be reached. Remote modules can be used to triple the monitoring lengths. That is why the monitoring system based on stimulated Brillouin scattering technology is selected for the project.

*Distributed strain and temperature sensors – sensing cables*

The majority of effort in the domain of distributed sensing was employed in the research and development of the reading units, while much less effort was employed to perfect the distributed sensors. Consequently, only a few types of distributed sensors for strain monitoring have been under development and they are at different advancement stages. When strain sensing is required, the optical fiber must be bonded to the host material over the entire length. The transfer of strain should be complete, with no losses due to sliding. Therefore, an excellent bond between the strain-sensing optical fiber and the host structure must be guaranteed. To allow such a good bond, the optical fiber is integrated within a cable-like shaped material, and integration procedures practically determine the performances of the sensor. The PI of this Payload project participated in several successful developments of distributed sensors and some of them are briefly presented in this section along with the work of other researchers.

Acrylate coated optical fiber was embedded in the cylindrical plastic coating cable (Bennett 2008) with a typical diameter of 0.9 mm. This sensing cable has good sensing performance for lower levels of measured strain, and has considerably low costs (~0.3 US$/m). However, it is delicate to install due to fragility (Bennett 2008), thus the costs of installation and protection can be elevated. The use of acrylate coated fibers can moderate its long-term performance at higher strain levels.

Polyimide coated optical fiber is embedded within the thermoplastic composite tape in a manner similar to the reinforcing fiber integration in composite materials (Glisic and Inaudi, 2003). The typical cross-section width of the tape is in the range of 10–20 mm while the thickness of the tape can be as low as 0.2 mm. The sensing tape was applied to an underground pipeline, concrete dam, and a steel bridge (Glisic and Inaudi 2007). Further research was performed on this sensor in order to develop a method for detection and localization of cracks (Ravet et al. 2009). This sensor had shown a very good performance in terms of high strain measurements and installation, but it features relatively large optical losses generated during the manufacturing process and consequently it suffices for monitoring of relatively short lengths (typically few hundreds of meters per channel). The cost of this sensor is approximately 23 UD$/m.

Four acrylate coated optical fibers were integrated in a strong nylon ribbon reinforced with steel wires, and then were employed in-field in a geotechnical application (Klar et al. 2006). This sensing cable has a good sensing performance for low strain levels, but it has elevated production costs (~30 USD/m). Surface installation of this cable can present some difficulties due to stiffness provided by reinforcing steel wires. The use of acrylate coated fibers can moderate long-term performance at higher strain levels.

Several optical fibers can be integrated in a thicker profile that combines strain and temperature sensors in a single package (Inaudi and Glisic, 2005). This sensor consists of two bonded and two free single-mode optical fibers embedded in a polyethylene thermoplastic profile. The bonded polyimide coated fibers are used for strain monitoring, while the free acrylate coated fibers are used for temperature measurements and to compensate temperature effects on the bonded fibers. For redundancy, two fibers are included for both strain and temperature monitoring. The size of the profile makes the sensor easy to transport and install by fusing, gluing or clamping. The sensor is designed for use in environments often found in civil, geotechnical, and oil and gas applications. The profile sensor was embedded in soil in order to detect and localize settlements and ground movements. The results of tests confirmed its suitability for this purpose (Belli et al. 2009). This sensing profile has a good sensing performance, it features significantly lower optical losses, and can be used for monitoring of considerably larger lengths, typically of several kilometers per channel. Cost of this sensing cable is 18 US$/m.

The temperature-sensing cables are designed for distributed temperature monitoring over long distances. They consist of several single-mode optical fibers contained in a stainless steel loose tube, protected with stainless steel armoring wires and an optional polymer sheath. The stainless steel and polymer protections provide high mechanical and additional chemical resistance. These components can be differently combined in order to adapt the cable to the required performance and application. Temperature sensing cables can be used in a wide range of applications that require distributed temperature sensing, and in particular can be used for leakage detection of buried pipelines (Inaudi et al. 2007).

*Conclusions*

Four different distributed strain sensing cables were identified and their performance is summarized in Table 4.

Table 4: Comparison of distributed strain sensing cables.

| Cable type | Strain measurement long-term performance | | Wide crack (damage) perform. | Fragility | Maximal length of cable per channel | Tested on pipelines | Approx. costs [US$/m] |
|---|---|---|---|---|---|---|---|
| | Low strain | High strain | | | | | |
| Cable 0.9mm | Good | Moderate? | Poor? | Very high | Some km? | No | 0.30 |
| Tape | Very good | Very good | Very good | Moderate | < 0.3 km | Yes | 23 |
| Ribbon | Good | Moderate? | Good? | Low | Some km? | No | 30 |
| Profile | Good | Moderate | Good? | Low | 4 to 6 km | No | 18 |

? – Information not available.

Based on the properties presented in Table 4 one can conclude that an ideal (mature) distributed strain sensing cable for monitoring of pipeline is not available, but from the price, performance, and installation points of view, the best candidates are tape-like and profile-like sensors. Also, a new sensor, developed for the purpose, should be envisaged.

In spite of the relatively high cost of the reading unit (two channels) of stimulated Brillouin scattering based fiber optic system (US$ 100,000 approximately, Bennett 2008), the potential to monitor continuously very large lengths with a single reading unit upgraded with less expensive remote modules (few tens of kilometers for strain and few hundreds of kilometers for temperature) make this technology a potentially economical for application in pipelines, where very large lengths are to be monitored. Expected simple installation of sensors, excellent longevity of optical fibers and the minimal maintenance of the reading unit make this technology promising for long-term monitoring.

Based on the literature review and the above considerations, development of a method for the assessment of earthquake-induced damage in pipelines caused by permanent ground deformation based on stimulated Brillouin FOS technology is proposed in this Payload project, in addition to and as a complement to the methods proposed by NEESR award.

## 7. Research Program Justification, Plan, and Expected Outcomes

### *Justification*

The importance of the real-time assessment of the pipeline structural health condition after an earthquake is introduced and highlighted in Section 5. Continuous structural health monitoring can significantly contribute to the real-time assessment of the pipeline condition after an earthquake, notably for buried pipelines, which cannot be conveniently assessed from the surface. Scientific and technological achievements in several branches of engineering, such as material engineering, telecommunications, informatics, and electrical engineering, made possible realization of monitoring systems capable of a real-time continuous operation, measurement, and transmission of large amounts of data expected from large structures such as pipelines.

NEES award project that will host this Payload project proposes a completely novel and very innovative approach in the domain of pipeline monitoring – the use of wireless intelligent sensors (with embedded damage detection algorithms) that are based on detection of damage induced changes in pipeline material properties (where the pipeline material is actually used as transducer).

This Payload project proposes another, alternative and complementary approach based on the use of the distributed fiber-optic sensing technology. The pioneering application was made on buried pipelines (Glisic and Inaudi 2007) and ground movements (Belli et al. 2009), and both confirmed the applicability of the technology. However, a method for evaluation of the pipelines' structural health condition under the earthquake-induced PGD using distributed FOS technology has not yet been developed, and this will be the aim of this Payload project.

The FOS are electrically passive and immune to electro-magnetic fields. Consequently, they can be installed onto the same specimens as those used in the NEESR award project, and they can be tested in parallel with the sensors developed in NEESR award project. Simultaneous measurements made on the same specimen provide for a great possibility to compare the results obtained using different monitoring systems (NEESR award's electrical probing and acoustic emissions, and Payload's distributed FOS) and can help deepen the knowledge concerning the pipeline damage and failure modes, they can serve as a means of validation for developed sensors and methods and help identify directions for improvement.

### *Plan*

<u>Introduction</u>

Buried pipelines exposed to earthquakes can be damaged in two ways: (a) due to wave propagation and (b) due to permanent ground displacement (PGD). The research of NEESR award and this Payload focuses on the latter. Primary forms of PGD are the following: (i) surface faulting, (ii) land-sliding, (iii) differential settlement, and (iv) lateral spreading due to liquefaction. In the case of localized PGD the damage in the pipeline occurs in the neighborhood of the rupture in the soil, while in case of the spatially distributed PGD the damage may occur anywhere within the PGD area. The research of NEESR award and this Payload focuses on the localized PGD.

Considering construction methods, three types of pipelines can be identified: (I) continuous pipelines, (II) segmented gravity pipelines, consisting of short pipe segments, and (III) segmented pressure pipes, consisting of longer pipe segments. Continuous pipelines are mostly made of steel, while segmented pipelines are mostly made of concrete. While continuous pipelines have "smooth" external surface, the "smoothness" of segmented gravity pipelines is interrupted by "irregularities" at joints; finally segmented pressure pipes may also have smooth surface, if metallic sleeve and metallic bell-and-spigot joint are incorporated. Each type of a pipeline has a different failure mode under the localized PGD, as given in Table 5.

Distributed fiber-optic technology based on stimulated Brillouin scattering is proposed for real-time automatic monitoring of buried pipelines. The monitoring system consists of (1) distributed fiber-optic sensors (FOS), (2) connecting cables, (3) reading units with remote modules, and (4) managing software installed on the reading unit (see Figure 2). The FOS can measure and localize both strain and temperature. FOS can be attached to the pipe, but it can also be simply laid in neighboring soil. Strain FOS can provide strain change distributions along the pipe, the measure/amount of overall straining, bending or torsion in the cross-sections, and qualitative strain and displacement changes in the soil. Temperature FOS can provide temperature change distributions along the pipe and in the soil. Damage to the pipeline can be detected and localized directly, by strain FOS as excessive straining and deformation or cracking of the pipe, or indirectly, either by detection of movement in the soil (using strain FOS), or by detection of change in the thermal properties of the pipeline surroundings due to leakage (using temperature FOS). Direct or indirect damage detection requires combination and implementation of different damage detection algorithms.

Table 5: Pipeline types, physical appearance of external surface and failure modes under localized PGD.

<table>
<tr><th>Pipeline type</th><th>External surface (where the sensor is to be installed)</th><th colspan="2">Most common failure modes</th></tr>
<tr><td>Continuous pipe</td><td>Smooth</td><td colspan="2">Tensile failure<br>Kinking (wrinkling or local buckling)<br>Beam buckling<br>Welded slip joint failure</td></tr>
<tr><td>Segmented gravity pipe</td><td>Irregular (not smooth)</td><td rowspan="2">Axial pull-out failure<br>Crushing of bell-and-spigot joints<br>Circumferential flexural failure<br>Joint rotation</td><td>Majority of failure at joints</td></tr>
<tr><td>Segmented (lined) pressure pipe</td><td>Smooth or irregular</td><td>More mid-spans failures</td></tr>
</table>

Pioneering applications of distributed FOS in the pipeline and soil monitoring were performed, but the proven, mature, technology, which is ready for application, does not exist. New sensors and installation procedures are to be developed. The type of the pipeline determines how the distributed FOS can be (or cannot be) installed. For example, in the case of continuous pipelines, strain FOS can be bonded along the entire length of the pipe, while in the case of segmented pipes this is not possible due to joints. For the latter it may be more appropriate to bond the sensor every meter of two, or to simply lay the sensor in the ground along the pipe. Also, for the continuous pipelines, the expected failure modes lead us to believe that the failure can be detected using parallel distributed sensors along the pipe (as seen in Table 5), while segmented pipes require different sensor topologies due to possible rotations of the joints and circumferential bending.

The aim of this Payload project is to develop a method for implementation of a distributed fiber-optic system to the pipelines in order to provide reliable means for real-time, automatic or on-demand, assessment of pipelines subject to earthquake-induced permanent ground displacement. The work encompasses four tasks: (1) development of appropriate sensor topologies for different pipe types, (2) development of new sensors and appropriate installation procedures, (3) development and implementation of damage detection algorithms, and (4) validation through tests. The proposed FOS technology and its applications were the topics of PI's previous research (as seen in the references), and demonstrated PI's expertise in this domain.

*Task 1: Determination of appropriate sensor topologies based on numerical modeling*

The capability of distributed FOS to reliably detect and localize damage depends on their topology, and more specifically, on their total number and position on the pipeline and in the soil. Topology of sensors depends on the expected pipe failure mode, which depends on the pipe type (as shown in Table 5). For example, parallel sensor topology is likely to detect bending of continuous pipes, but it is not likely to detect torsion in the joints of a segmented pipe. In the latter case, straining of parallel sensors due to torsion will either damage the sensors, or can be incorrectly interpreted, thus it may be more appropriate to incline the sensors with respect to the pipe longitudinal axis (see Figure 3).

The capability of distributed strain sensors to detect and localize settlement in the soil depends on the sensor-soil interaction. It also depends on the distance of the sensor from the pipe and on the position of the sensor with respect to the pipe, i.e., whether the sensor is above, below or on a side of the pipe. If the sensor-soil interaction is not satisfactory, the use of so called geo-textile (technical textile for soil reinforcement) will be considered in order to enhance the interaction implementation.

In addition, it is important to determine the minimal number of sensors necessary to achieve the objective, but also to recommend the number of sensors (ensuring redundancy) for a reliable, long-term operation. Some examples of applications of different sensor topologies from previous research highlight the importance of appropriate selection of topology. These examples are summarized in Figure 3.

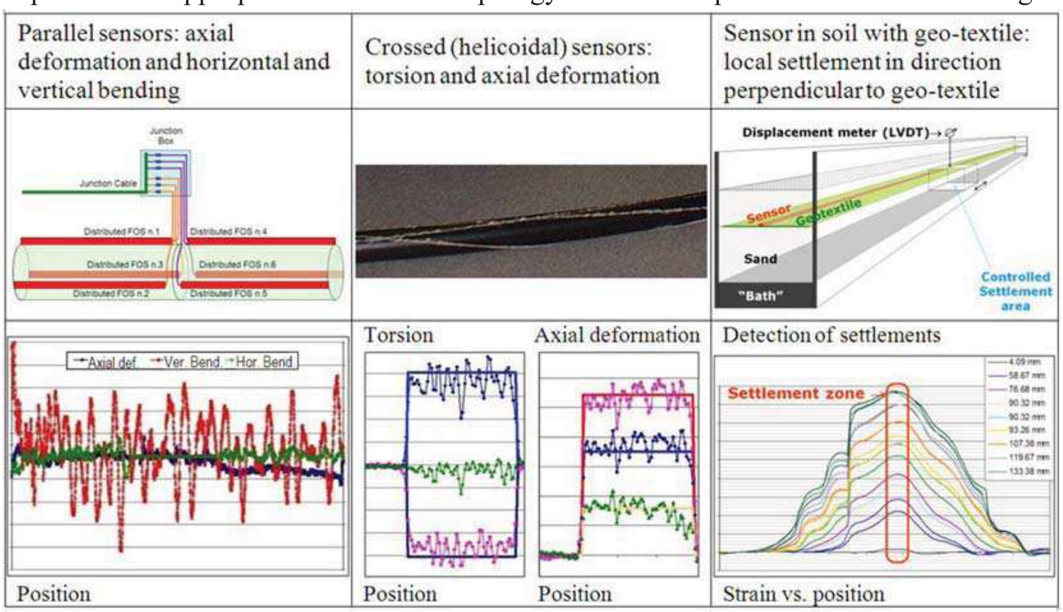


Figure 3: Correlation between different topologies of distributed sensors and monitored parameters (results taken from previous research) (Glisic and Inaudi 2007, Belli et al. 2009).

Numerical and analytical analysis of soil-pipe interaction planned in NEESR award Task 1 will provide information on stress and strain generation in pipelines due to PGD and due to the damage modes and patterns. The results of the analysis will be used to determine topologies of sensors to be deployed on the pipes for different pipe types. Similar analysis can be performed for the interaction between the soil and the sensors which will be deployed in soil. Results of this analysis will serve as an input to determine the topology of sensors (including sensor position with respect to the pipe, and its distance from the pipe) and the necessity to use geo-textile in order to improve the interaction quality. The numerical tools and the numerical models built for soil-pipe interaction in the framework of the NEESR award are recommended to be used for the analysis of soil-sensor interaction.

Selection of topologies, simplified analysis, and preliminary tests will be performed in the Princeton SHM Laboratory. Validation tests on pipe specimens will be performed at the Cornell NEES site.

*Task 2: Development of new sensors and installation procedures*

Although the tape and profile sensing cables were identified as good candidates for pipeline monitoring, a new, for this purpose developed, distributed fiber optic sensor, is also envisioned in order to overcome the important shortcomings of the tape and profile sensors. High optical losses are associated with the tape sensors and relatively elevated costs apply to both tape and profile sensors. A reasonable alternative is a new low cost sensor (~5 US$/m) which exhibits a moderate but reliable measurement performance in the long-term, and is mechanically robust enough to provide for a safe low cost installation. Compromise is to be made between the measurement performance (which depends on the quality of internal interaction between the cable packaging and the optical fiber), the measurable length range of the sensor (which depends on cumulative optical losses generated by internal interaction and installation), and manufacturing costs (better internal interaction is associated with higher cost). Different types of sensing cables will be analyzed: cables with fully bonded and free fibers, cables with loosely bonded and free fibers and cables with only free fibers. Different types of optical fiber coatings will be considered (acrylate vs. polyimide), and manufacturing processes involving inexpensive packaging materials will be examined (pultrusion vs. components assembling).

The type of pipe influences the installation procedures. Sensors can be bonded along continuous and smooth segmented pipelines (as seen in Table 5), but this manner of installation is not fully applicable for irregular segmented pipelines. Irregularities on the external surface make obstacles for sensing cables that should be detoured in order to avoid excessive bending of the cables. Excessive bending may introduce optical losses in the sensing fibers. A possible way to detour the irregularities is to install the sensing cable by clamping or bonding at discrete points. An example of distributed strain FOS bonded along the continuous metallic pipe is given in Figure 4a. An example of a distributed strain FOS clamped to the concrete surface is given in Figure 4b (Glisic and Inaudi 2007).

Figure 4: Examples of distributed sensing cables installation (a) full bonding and (b) clamping.

A bonded sensor may be damaged by cracking in a pipe if the adhesive is not properly selected and applied. Recent research (Ravet et al. 2009) demonstrated that with an appropriate selection of the adhesive damage in the sensor due to pipe cracking can be avoided. A sensing cable which is clamped or bonded at discrete points is not exposed to risk in the case of cracking, since the crack opening will not directly affect the cable. For sensing cables installed in the soil, the necessity to use the geo-textile to enhance the interaction between the cable and the soil will be evaluated. Appropriate installation procedures will be developed based on real needs related to the selection of the pipe material, pipe shape, and other restrictions, such as the allowable damage of the pipe due to the sensor installation (e.g. drilling holes for fastenings) and the necessary protection to prevent the damage of the sensing cables.

New sensor and installation procedures will be developed and tested in the Princeton SHM Laboratory through a series of reduced scale tests, and they will be validated during the tests on pipe specimens at the Cornell NEES site.

*Task 3: Method validation testing*

Tests scheduled in the NEESR award Task 3 – Soil-pipe interaction large-scale testing will accommodate method validation tests. Tight collaboration and coordination are necessary for efficient planning and successful realization of tests. Validation will be performed at the Cornell NEES site.

The distributed sensing system has typical spatial resolution of 1 m, but for shorter lengths of sensors it can be decreased to 0.5 m. In such circumstances the minimal pipe specimen length is to be at least three times longer i.e. minimum 1.5 m (~5 feet), and this is in accord with the specimen length established by the NEESR award. The spatial resolution is a configuration parameter of the reading unit that can be simply adjusted before the measurement.

The measurement time depends on the measurement range and desired accuracy, and it typically varies between 30 sec and 5 minutes per channel for a static reading unit. Provided that the length of the testing bed is 10 meters, and the total length of each sensor will not exceed 15 m, all the sensors can be enchained and connected to a single channel and read simultaneously. Besides the static reading unit (commercially available and field verified) a dynamic reading unit with 1 Hz sampling is under development and will be used during the tests, if available.

The sensors will be installed onto the external walls of pipe specimens forming topologies developed in Task 1 and using the installation procedures developed in Task 2. Depending on the availability of space on the pipe specimen, preferably two different distributed sensors of the same type will be tested simultaneously (e.g. tape or profile packaged sensor will be tested in parallel with the newly developed sensors) in order to assess and compare their performances in terms of strain measurements, crack sensitivity, and quality of installation.

Concrete gravity pipe is not included in the tests (see matrix of testing in Table 6), but the short segmented pressure pipe (5 feet) is expected to undergo the majority of failures at joints, similar to the gravity pipe; that is why both installation procedures will be tested on those specimens, for the smooth and the irregular external surfaces. Only the installation procedure for smooth surfaces will be applied to other pipe specimens (continuous, steel, and long segmented, concrete).

The length of the test bed is approximately 10 meters, but in order to minimize the influence of border effects on the measurements, a length of approximately 15 meters is chosen for the sensors. At least one extremity of the sensor must be accessible for measurements, but it is recommended to have accessibility to both extremities (see Figure 5). Sensing cables will be installed both onto the pipeline and in the soil. The matrix of testing is given in Table 6 and a general schematic drawing of the test configuration is given in Figure 5.

Table 6: The matrix of validation testing in NEES facility.

| Pope type | Strike slip (horizontal) fault angle α | | | Vertical faulting angle β | Sensors topology (tentative, will be adjusted to outcomes of Task 1) | Installation procedure (tentative, will be adjusted to outcomes of Task 2) |
|---|---|---|---|---|---|---|
| | 30° | 60° | 90° | 90° | | |
| Concrete pipe ~1.5 m (5’) segments | 2 SoS | 2 SoS | 2 SoS | 2 SoS* | For failure at joints | For smooth and for irregular surfaces |
| Concrete pipe 2.4 m (8’) segments | 1 SoS | 1 SoS | 1 SoS | 1 SoS | For mid-span failures | For smooth surfaces |
| Steel pipe (continuous) | 1 SoS | 1 SoS | 1 SoS | 1 SoS | For continuous pipe | For smooth surfaces |

*n SoS - number of sets of sensors to be used in each test

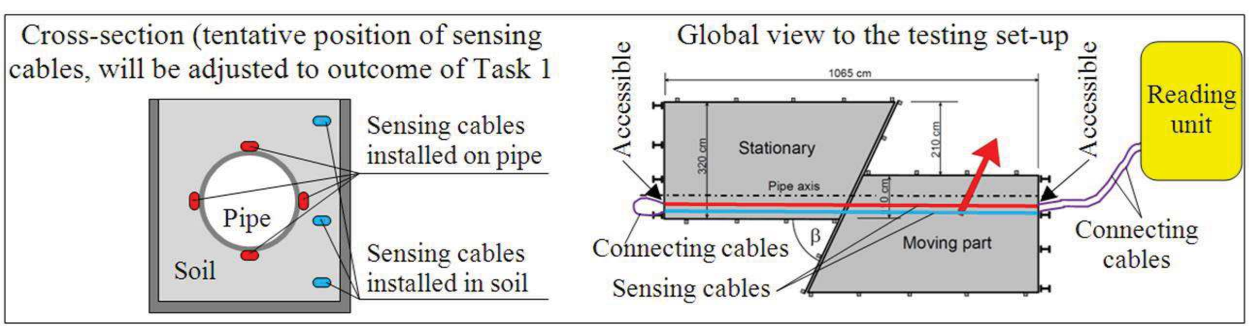


Figure 5: General schematic drawing of the test.

*Task 4: Data analysis*

Primary data analysis consists of filtering out the outliers and the noise, interpretation and correlation with PGD load cases and visual inspection (for crack occurrence) of the pipe after each test. Primary data analysis will help identify data patterns characteristic for each performed PGD scenario and whether the FOS system was able to detect the damage in a direct or an indirect manner.

As a second step of data analysis, different comparisons will be performed:

- Comparison with results obtained by strain-gages installed in the framework of the NEESR award Task 3; this comparison will help evaluate the FOS system in terms of the measurement performance and the installation method.
- Correlation between the FOS installed on the pipeline with those installed in soil; this correlation (if any) will help determine whether two FOS installations are redundant or complementary; in case of redundancy, we will evaluate which installation performs better and whether it can be used alone (for a more economical solution).
- Correlation with results obtained using novel wireless technology developed in the framework of the NEESR award project; this comparison will help determine which technology is more sensitive for which PDG scenario.
- Comparison with numerical modeling performed in Task 1; it will help better understand processes of soil-pipe interaction and soil-sensing cable interaction, and improve the numerical modeling.

***Expected outcomes***

The following outcomes are expected from this Payload project:

- Large-scale test data with a behavior of buried pipelines subject to PGD including longitudinal and cross-sectional distributions of strain, bending, and torsion, and crack detection and localization.
- Large-scale test qualitative data with a behavior of soil in the neighborhood of buried pipelines subject to PGD, including displacement detection and localization.
- Results of numerical and analytical analysis of soil-sensor interaction.
- Developed method for assessment of damage on buried pipelines after earthquake-induced PGD, based on distributed FOS including:
    - Development of a new sensor type;
    - Sensor topologies on pipe and/or in the soil;
    - Installation procedures;
    - Damage detection and data analysis algorithms.

In addition, evaluation of performance of the dynamic reading unit will be made if the reading unit is available at the time of the Payload project realization.

# 8. Education, Outreach, and Technology Transfer Activities

As recommended in NSF 09-524 Program Solicitation Document, the PI will focus only on the few major activities stemming from the proposal. Having provided that main topics of the project are the assessment of the health condition of the pipeline, the major targeted groups for the education, outreach, and technology transfer activities will be students, both undergraduate and graduate, and various professionals such as responsible mangers, operational engineers, policy makers, and equipment producers and vendors.

PI's experience is that the knowledge, potential, and culture of structural health monitoring are not sufficiently spread among professionals, which is mainly due to the fact that this young discipline is not included in regular undergraduate and graduate courses. That is why the results of the project will be used to educate the future professionals, i.e. graduate and undergraduate students. Analytical approach on pipeline structural behavior, developed fiber-optic technology including both scientific background and practical implementation challenges, and the benefits from using the developed method, will be presented through courses, lectures, seminars, workshops, conferences, a website, posters, and published papers. In particular, a network of universities (including non-PhD-granting Merrimack College, MA) established during the project realization with NEESR award participants will be used to increase the audience. Since the proposed project involves multidisciplinary research, not only the students of civil and structural engineering will be targeted, but also the students of other branches of engineering such as the environmental, mechanical, materials science, and geotechnical, the students of physics and applied optics, as well as the students of political and social sciences, as the future potential policy-makers.

At the same time, the PI will ensure an outreach to the current professionals such as managers and operational engineers from the involved industries, infrastructure administration, crisis and rescue departments, and policy makers, in order to make them aware of technological possibilities and the manifold benefits of the developed method, to create opportunities for implementation of the method on the real pipelines. Taking into account relatively limited resources allocated for Payload projects, the outreach activities for this targeted group will be conducted through the website, published papers and web-seminars (so-called webinars). Similar means will be used to communicate the results of the project to producers of monitoring systems in order to identify the possibilities for the technology transfer.

## 9. Data Archiving and Sharing Plan

***General***

Data archiving and sharing will be embedded in the plan of the NEESR award and will follow the same principles as presented in Section 9 of the NEESR award project description document, fully respecting guidelines proposed for upload to the NEEScentral.

***Data and documentation archiving formats, schedule, and sharing***

Data archiving and sharing schedule is summarized in Table 7.

Table 7: Data archiving and sharing schedule.

| Production, archiving, and release of data | | Year 1* | | | | Year 2* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| 1$^{st}$ series of tests | Unprocessed data: production, repository and NEEScentral archiving for internal release | | Jun ’10 | | | | | | |
| | Processed data: NEEScentral archiving for internal and public release | | | | Dec ’10 | | Jun ’11 | | |
| 2$^{st}$ series of tests | Unprocessed data: production, repository and NEEScentral archiving for internal release | | | | | | Jun ’11 | | |
| | Processed data: NEEScentral archiving for internal and public release | | | | | | | Nov ‘11 | Jan ’12 |

*Quarters indicates project year quarters, not calendar quarters; beginning is planned for February 2010.
■Light-gray color shading indicates internal release of data.
■Dark-gray color shading indicates public release of data.

Unprocessed data will be stored to the repository and the NEES central, and made available to all participants (including the NEESR award) immediately after the test. The unprocessed data will be formatted in TXT files, one file per measurement, containing basic data related to the measurement (date, time, parameterization, etc.) and two columns: the first column containing positions of measurement points along the sensor and the second column containing the Brillouin frequency values. A PDF file with detailed explanations on file contents will be provided.

Processed data will be stored in NEEScentral no later than six months after the test completion and will be made available to the public no later than 12 months after the completion. The processed data will be delivered in an XLS format with accompanying documentation in the PDF and PPT formats. The documentation will contain detailed descriptions of tests and equipment in order to the guarantee understandability and reproducibility of the tests.

Data will be shared through the NEESCentral, but also on the websites developed for this purpose at Princeton University (Payload project) and at the University of Michigan (NEESR award).

***Limitations and restrictions***

In general, no restrictions on the use of data will be imposed. However, the experimental nature of the data will be highlighted, therefore the researchers and the NEES will decline any and all responsibility for the use of the data through a disclaimer. A requirement of acknowledgement will be imposed on the use of the data.

## 10. Payload Opportunities

In accord with the program solicitation NSF 09-524 Payload applications can be made only for Core Research and Simulation Development projects and, consequently, this Payload project does not offer further Payload opportunities.

## 11. Project Implementation Plan

Project schedule and functional budget table are presented in Table 3. Data archiving and sharing schedule is given in Table 7. Testing plan for the NEES site is shown in Table 6. The role of the PI is presented in Table 1, and is described below in detail.

Professor Glisic has a strong background in the domain of structural health monitoring using fiber optic technologies. He will be responsible for the development of the proposed method including the development of a monitoring strategy to be applied for pipelines, development of new fiber optic sensors, their installation procedures, and data analysis and damage detection algorithms. His background and practical involvement in full-scale projects will help to identify and overcome key challenges.

One graduate student will be involved in the project for two years at Princeton University. He will be involved in each phase of the project with a main focus on the parametric studies for Tasks 1 and 2, conception and building of sensor prototypes, and execution of tests to be performed in the framework of Tasks 2 and 3 (at the NEES site), and data handling and processing in Tasks 2, 3 and 4. His salary will be partially ensured through the project funding and partially by Princeton University (see Budget Justification Sheet).

One undergraduate student will assist with Task 2 each year (in total two undergraduate students) at no additional costs.

## 12. Project Risk Mitigation Plan

As specified in NEESR Solicitation NSF 09-524 (page 12), the risk mitigation plan is presented as Special Information and Supplementary Documentation.

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# Biographical Sketch

## Branko Glisic

Department of Civil and Environmental Engineering
Princeton University, E330, EQuad
Princeton, NJ 08540
Tel: 609 258 8278
Fax: 609 258-2760
E-mail: bglisic@princeton.edu

## Education

| | | |
|---|---|---|
| University of Belgrade, Serbia | Faculty of Civil Engineering | BS, MS 1994 |
| University of Belgrade, Serbia | Faculty of Mathematics | BS, MS 1996 |
| Swiss Federal Institute of Technology, Lausanne (EPFL) | Dpt. of Civil Engineering | PhD 2000 |

## Appointments

| | |
|---|---|
| 2009-present | Assistant Professor, Civil and Environmental Engineering, Princeton University |
| 2000-2008 | R&D Manager, SMARTEC SA, Manno, Switzerland |
| 1996-2000 | PhD Student, Civil Eng., Swiss Federal Institute of Technology, Lausanne (EPFL) |
| 1995-1996 | Teaching Assistant, Faculty of Civil Engineering, University of Belgrade, Serbia |

## Publications

***Closely related to this project***

Belli, R., Glisic, B., Inaudi, D., Gebreselassie, B. (2009). Smart Textiles for SHM of geostructures and Buildings. *SHMII-4, Intl. Conf. on Structural Health Monitoring of Intelligent Infrastructure,* Zurich, Switzerland.

Ravet, F., Briffod, F., Glisic, B., Nikles, M., Inaudi,D. (2009). Sub-millimeter crack detection with Brillouin based fiber optic sensors. *IEEE Sensors Journal, Special Issue on Sensor Systems for Structural Health Monitoring* (to be published in May 2009)

Inaudi, D. and Glisic, B. (2008) Distributed fibre-optic sensing for long-range monitoring of pipeline. *The Monitor – Publication of International Society for Structural Health Monitoring of Intelligent Infrastructure*, March 2008: 35-41 (Awarded Paper).

Glisic, B. and Inaudi, D. (2007). *Fibre Optic Methods for Structural Health Monitoring*. John Wiley & Sons, Ltd.

Glisic, B. and Inaudi, D. (2003). Sensing tape for easy integration of optical fiber sensors in composite structures. *Proc. of 16th International Conference on Optical Fiber Sensors,* We 3-8, Nara, Japan.

***Other publications***

Viviani, M., Glisic, B., Scrivener, K.L., Smith, I.F.C. (2008). Equivalency points: Predicting concrete compressive strength evolution in three days. *Cement and Concrete Research,* No. 38*: 1070–1078.*

Glisic, B., Posenato, D., Inaudi, D., Figini,A. (2008). Structural health monitoring method for curved concrete bridge box girders. *Proc. of 15$^{th}$ SPIE's International Symposium, Conference on Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems,* Paper 6932-6, San Diego, USA.

Viviani, M., Glisic, B., Smith, I.F.C. (2007). Separation of thermal and autogenous deformation at varying temperatures using optical fiber sensors. *Cement and Concrete Composites, Elsevier,* Volume 29, Issue 6: 435-447.

Glisic, B., Inaudi, D., Lau, J.M, Ng C.T., Yap T.Y. (2007),Large scale lifespan monitoring of high-rise buildings using long-gage fiber optic sensors, *SHMII-3, The 3$^{rd}$ Intl. Conf. on Structural Health Monitoring of Intelligent Infrastructure,* Vancouver, Canada.

Viviani, M., Glisic, B., Smith, I.F.C. (2006). System for monitoring the evolution of the thermal expansion coefficient and autogenous deformation of hardening materials. *Journal of Smart Materials and Structures,* Institute of Physics, London, Smart Mater. Struct. 15: N137-N146.

## Synergistic Activities

Co-author of the book on structural health monitoring entitled “Fibre Optic Methods for Structural Health Monitoring”, presenting universal SHM methods, fiber-optic technologies and real on-site applications. Developed five day courses on SHM for practitioners and universities, invited lectures at several universities, governmental institutions and companies in Europe and Asia. Development of two graduate and one undergraduate course, and the SHM Center at Princeton University. Member of International Association of Bridge and Structural Engineers (IABSE). Responsible and co-responsible for three international R&D projects funded by European Commission.

## Collaborators & Other Affiliations

***Collaborators within last 48 months***

*Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland*: Karen Scrivener, Ian Smith.

*Housing and Development Board (HDB), Singapore*: Joo Ming Lau, Chun Tat Ng, Tiem Yew Yap.

*Ministry of Transportation of Quebec, Canada*: Jean-Francois Laflamme and Martin Talbot.

*SMARTEC SA, Manno, Switzerland*: Riccardo Belli, Nicoletta Casanova, Angelo Figini, Daniele Inaudi, Luca Manetti, Daniele Posenato, Roberto Walder.

*Omnisens SA, Morges, Switzerland*: Fabien Briffod, Marc Nikles, Fabien Ravet.

*ROCTEST Ltd., Saint-Lambert, Quebec, Canada*: Caroline Hamel, Nicolae Miron, Eric Pinet.

*Tecnomare SpA, Venice Marghera, Italy*: Stefano Cenedese, Francesco Gasparoni, Maurizio Zecchin.

*Other*: Miran Antauer,*Telem d.o.o, Maribor, Slovenia*; Merit Enckell, *COWI A/S, Kongens Lyngby, Denmark*; Berhane Gebreselassie, *University of Kassel, Germany*; Frank Myrvoll, *Norwegian Geotechnical Institute (NGI), Oslo, Norway*; Fredrik Persson, *Minova-Bemek, Stocholm, Sweden*.

***Graduate Advisor***

Leopold Pflug, Professor Emeritus, Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland.

***PhD Thesis Advisor (total number of advised PhD students is one)***

Marco Viviani, High School of Engineering and Management of Canton Vaud, Yverdon-les-Bains (HEIG-VD), Switzerland (thesis made at the EPFL).

# SUMMARY PROPOSAL BUDGET

YEAR 1

| | | | | | | |
|---|---|---|---|---|---|---|
| ORGANIZATION<br>**Princeton University** | | | | FOR NSF USE ONLY<br>PROPOSAL NO. | DURATION (months)<br>Proposed | Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR<br>**Branko Glisic** | | | | AWARD NO. | | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. **Branko Glisic - Asst Professor** | 0.00 | 0.00 | 0.00 | $ 0 | $ |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |
| 5. | | | | | |
| 6. ( 0 ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | 0 | |
| 7. ( 1 ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 0.00 | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | 0 | |
| 3. ( 1 ) GRADUATE STUDENTS | | | | 4,000 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 4,000 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 4,000 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | 4,550 | |
| 2. FOREIGN | | | | 0 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 0<br>2. TRAVEL 0<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 0 ) TOTAL PARTICIPANT COSTS | | | | 0 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 12,500 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 1,000 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 0 | |
| TOTAL OTHER DIRECT COSTS | | | | 13,500 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 22,050 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>**MTDC (Rate: 61.0000, Base: 22049)** | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 13,450 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 35,500 | |
| K. RESIDUAL FUNDS | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 35,500 | $ |
| M. COST SHARING PROPOSED LEVEL $ 0 | AGREED LEVEL IF DIFFERENT $ | | | | |

| | | | |
|---|---|---|---|
| PI/PD NAME<br>**Branko Glisic** | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION | | |
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

1 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

# SUMMARY PROPOSAL BUDGET

YEAR 2

| | | | | | |
|---|---|---|---|---|---|
| ORGANIZATION<br>**Princeton University** | | | | FOR NSF USE ONLY<br>PROPOSAL NO. | DURATION (months)<br>Proposed / Granted |
| PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR<br>**Branko Glisic** | | | | AWARD NO. | |

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. **Branko Glisic - Asst Professor** | 0.00 | 0.00 | 0.00 | $ 0 | $ |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |
| 5. | | | | | |
| 6. ( 0 ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | 0 | |
| 7. ( 1 ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 0.00 | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | 0 | |
| 3. ( 1 ) GRADUATE STUDENTS | | | | 15,975 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 15,975 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 15,975 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | 4,550 | |
| 2. FOREIGN | | | | 0 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 0<br>2. TRAVEL 0<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 0 ) TOTAL PARTICIPANT COSTS | | | | 0 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 12,500 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 1,000 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 9,688 | |
| TOTAL OTHER DIRECT COSTS | | | | 23,188 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 43,713 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)<br>**MTDC (Rate: 61.0000, Base: 34025)** | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 20,755 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 64,468 | |
| K. RESIDUAL FUNDS | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 64,468 | $ |
| M. COST SHARING PROPOSED LEVEL $ 0 | AGREED LEVEL IF DIFFERENT $ | | | | |

| | | | |
|---|---|---|---|
| PI/PD NAME<br>**Branko Glisic** | FOR NSF USE ONLY<br>INDIRECT COST RATE VERIFICATION | | |
| ORG. REP. NAME* | Date Checked | Date Of Rate Sheet | Initials - ORG |

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

# SUMMARY PROPOSAL BUDGET

Cumulative

| FOR NSF USE ONLY | | |
|---|---|---|
| PROPOSAL NO. | DURATION (months) | |
| | Proposed | Granted |
| AWARD NO. | | |

ORGANIZATION
**Princeton University**

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
**Branko Glisic**

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets) | NSF Funded Person-months CAL | ACAD | SUMR | Funds Requested By proposer | Funds granted by NSF (if different) |
|---|---|---|---|---|---|
| 1. Branko Glisic - Asst Professor | 0.00 | 0.00 | 0.00 | $ 0 | $ |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |
| 5. | | | | | |
| 6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE) | 0.00 | 0.00 | 0.00 | 0 | |
| 7. ( 1 ) TOTAL SENIOR PERSONNEL (1 - 6) | 0.00 | 0.00 | 0.00 | 0 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| 1. ( 0 ) POST DOCTORAL SCHOLARS | 0.00 | 0.00 | 0.00 | 0 | |
| 2. ( 0 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | 0.00 | 0.00 | 0.00 | 0 | |
| 3. ( 2 ) GRADUATE STUDENTS | | | | 19,975 | |
| 4. ( 0 ) UNDERGRADUATE STUDENTS | | | | 0 | |
| 5. ( 0 ) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY) | | | | 0 | |
| 6. ( 0 ) OTHER | | | | 0 | |
| TOTAL SALARIES AND WAGES (A + B) | | | | 19,975 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | 0 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C) | | | | 19,975 | |
| D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) | | | | | |
| TOTAL EQUIPMENT | | | | 0 | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS) | | | | 9,100 | |
| 2. FOREIGN | | | | 0 | |
| F. PARTICIPANT SUPPORT COSTS<br>1. STIPENDS $ 0<br>2. TRAVEL 0<br>3. SUBSISTENCE 0<br>4. OTHER 0 | | | | | |
| TOTAL NUMBER OF PARTICIPANTS ( 0 ) TOTAL PARTICIPANT COSTS | | | | 0 | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 25,000 | |
| 2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION | | | | 2,000 | |
| 3. CONSULTANT SERVICES | | | | 0 | |
| 4. COMPUTER SERVICES | | | | 0 | |
| 5. SUBAWARDS | | | | 0 | |
| 6. OTHER | | | | 9,688 | |
| TOTAL OTHER DIRECT COSTS | | | | 36,688 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 65,763 | |
| I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) | | | | | |
| TOTAL INDIRECT COSTS (F&A) | | | | 34,205 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 99,968 | |
| K. RESIDUAL FUNDS | | | | 0 | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 99,968 | $ |
| M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $ | | | | | |

PI/PD NAME
**Branko Glisic**

ORG. REP. NAME*

| FOR NSF USE ONLY | | |
|---|---|---|
| INDIRECT COST RATE VERIFICATION | | |
| Date Checked | Date Of Rate Sheet | Initials - ORG |
| | | |

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

## Budget Justification- Princeton University

The government generally allows a 4% per year escalation on direct costs and the University follows this guideline.

***Senior Personnel***

Princeton University fully supports the academic year salaries of Assistant Professors but makes no specific commitment of academic year time or salary to this particular research project.

***Salaries and Wages – Other Personnel***

Support is requested for 1 masters or post-general graduate student (at 50% time during the Year 2 academic year and 50% during the summers). For the first one and half years, the student will be supported by either research assistantships in another related project or teaching assistantships. Graduate School stipends are set by the Graduate School.

***Domestic Travel***

A total of $9,100 over 2 years is requested to cover several types of trips for:

1. The PI to attend the annual NEES Research & Development awardees meeting (2 trips)

| | |
|---|---|
| Airfare- location TBA, using Denver, CO (midpoint of US), as proxy | $ 350 |
| local transportation (car rentals, mileage, parking) | $ 110 |
| 3 housing per diems @ $135 | $ 405 |
| 3 meal per diems @ $46 (Univ rate for high cost localities) | $ 135 |
| Total/trip | $1,000 |

2. The PI to attend the CMMI Division's grantees meeting for 3 days (1 trip)

| | |
|---|---|
| Airfare- location TBA, using Denver, CO (midpoint of US), as proxy | $ 350 |
| local transportation (car rentals, mileage, parking) | $ 110 |
| 3 housing per diems @ $135 | $ 405 |
| 3 meal per diems @ $46 (Univ rate for high cost localities) | $ 135 |
| Total/trip | $1,000 |

3. The PI and graduate student to attend testing at Cornell NEES site (1 trip)

| | |
|---|---|
| Car- Princeton, NJ to Ithaca, NY (450 mi. roundtrip x $0.55/mi x 4) | $ 990 |
| 50 housing per diems @ $66.20 | $3.310 |
| 50 meal per diems @ $36 (Univ rate) | $1,800 |
| Total/trip | $6,100 |

***Materials and Supplies***

$25,000 is requested for materials and supplies. Of this amount, $16k will be used for rental fees of reading unit while remaining $8k will be used for development of sensors and installation procedures. In addition, $1k is requested for the shipping fees of material. The details are listed below.

| | Pieces | Cost/pc. | Discount | Cost |
|---|---|---|---|---|
| *Rentals* | | | | |
| Weekly rental of reading unit | 4 | $3,517.73 | 10% | $12,664 |
| Additional charge for short rentals | 4 | $ 946.91 | 100% | $ 0 |
| Rental of crack detection software | 1 | $7,890.88 | 100% | $ 0 |
| Weekly rental of dynamic reading unit | 1 | $4,116.98 | 10% | $ 3,705 |
| Subotal (see supplementary section for details) | | | | $16,369 |
| *Sensors* | | | | |
| Tape sensor, 60 m | 1 | $1,500.00 | 0% | $ 1,500 |
| Profile sensor, 60 m | 1 | $1,500.00 | 0% | $ 1,500 |
| New sensor prototypes, 60 m | 2 | $1,570.00 | 0% | $ 3,140 |
| Installation material | | | 0% | $ 1,500 |
| Subtotal | | | | $ 7,640 |
| *Shipping* | | | | |
| Shipping fees | | | | $ 991 |
| Grand Total | | | | $25,000 |

***Publication Costs/Documentation/Dissemination***

$2,000 is requested for the following: publications ($250), 4 webinars @ $100/session= $400, 1 poster @ $600, and 3 workshops/seminars at $250 each.

***Other***

Graduate School tuition is set by the Graduate School and includes mandatory health insurance fees. For sponsors that pay full indirect costs, Princeton University only charges half tuition for the graduate students. The Graduate School pays the remainder.

***Indirect Costs***

Indirect costs of 61% are collected based on the total direct costs less graduate school tuition. This rate was negotiated with the Department of Health and Human Services in an agreement dated July 9, 2008.

# Current and Pending Support

**(See GPG Section II.C.2.h for guidance on information to include on this form.)**

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Branko Glisic

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: None

Source of Support:
Total Award Amount: $ 0 Total Award Period Covered: 01/01/00 - 01/01/00
Location of Project:
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

# Facilities, Equipment, & Other Resources

***Large Displacement Facility for Lifeline Systems – NEES Site at Cornell University***

The facility at Cornell University was selected by the Team of NEESR award that will accommodate this Payload project. The NEES Large Displacement Facility at Cornell University is fundamental to the Payload project, since the soil-pipeline interaction is sensitive to the scale of the problem and the alteration of structural health condition of pipelines caused by ground motions cannot be tested on small segments of pipes.

The NEES site at Cornell University contains Large Displacement Lifeline Testing System supported by servo-hydraulic actuators and ancillary hydraulic equipment. All this equipment allows for simulations of ground movement as big as 1 m, which provides for full mobilization of soil-pipe specimen interaction.

Large quantities of soil necessary for full-scale tests are handled by a conveyor and soil storage system. The conveyor is used to move large quantities of soil from and to storage bins. The storage capacity is 40 to 45 cubic meters of soil used in movable split soil boxes.

Validation tests (Task 3) will be performed at the NEES Cornell site. The facility is equipped with a fiber optic conditioner (reading unit) for various point sensors (not distributed sensors) and the personnel is familiar with fiber optic technologies.

***SHM Laboratory at Princeton University***

The Structural Health Monitoring (SHM) Laboratory at Princeton University is a new laboratory created by the PI and aims to become a state-of-the-art laboratory with modern monitoring tools and sensor testing equipments based on advanced technologies. It will be a part of the SHM Center that will also contain a SHM knowledge unit and a SHM computer aided unit.

The laboratory will be raised to a functional level before the start of the project. It will contain benches and tools for assemblage and mechanical testing of sensors, climatic chamber and thermal baths for temperature cycling, and will be capable of conducting weathering exposure simulations and accelerated aging tests. Novel sensors and monitoring techniques will be validated through testing and compared with calibrated and proven ones.

The SHM Laboratory of the SHM Center will accommodate the small-scale test of topologies (Task 1), and development and pre-testing of sensors and installation procedures (Task 2).

# Project Risk Mitigation Plan

The PI is familiar with the Cornell NEES Safety Manual published on Cornell NEES Sites' web page (http://nees.cornell.edu/Safety Manual.htm). The project management team of the NEESR award that is accommodating this Payload project previously evaluated the risks related to their testing and the results are summarized in the NEESR award project description document. The risks related to deployment of distributed fiber optic sensing cables are analyzed here in accordance with the NEES Facilities User Guide made by NEESinc (Version 2.6 from February 04, 2006). The outline is given as follows.

The Payload project affects the equipment to be used by NEESR award in the following manner:

- Several distributed strain sensing cables will be physically attached to the pipe prototype over all the length (bonded or clamped);
- Several distributed strain and temperature sensing cables will be embedded in soil, with or without geo-textile for better soil-sensor interaction;
- All sensing cables must egress from one side of the test bed (preferably both extremities are to be accessible);
- Reading unit should be placed less than 15 m from the test bed and connected to the sensing cables by mean of connecting fiber-optic cable.

- Is there risk to equipment and to manufacturing the components of test assembly?

  Stiffness of fiber optic sensing cables is significantly lower than the stiffness of the pipes, consequently, it is not expected that presence of cables decrease the safety of equipment (with respect to conditions of test in frame of NEESR award testing).

- Is there risk of assembling the experimental configuration?

  The sensing cables will be either bonded or clamped to pipes. Bonding will be performed with tested adhesive that will not alter the properties of the pipe material. Clamping will be performed only if it does not alter the acoustic and electric properties of the pipe. When deploying the sensors, usual precautions will be made (protective cloth, gloves, goggles, and mask, must be used by personnel and more intensive aeration of the space might be necessary).

- Will experiments lead to expected damage patterns and are the simulations feasible?

  Heavy equipment of the pipe with strain sensing cables can increase stiffness of the pipe (e.g. several tape sensors) while the presence of some embedded cables may increase the stiffness of the soil (e.g. stainless steel reinforced cable laid in the soil, or non-reinforced cable laid in soil with geo-textile); these influences do not influence the results of Payload project (since reflect the reality) but if the change in stiffness is significant, they may alter the results of NEESR award; consequently, the influence of sensors presence of the sensor is to be modeled (Task 1) and if possible pre-tested, in order to minimize the risk of alteration of results of NEESR award. The number of sensors and their manner of installation will be adjusted to results of modeling and pre-testing.

- Handling of the sensing cables and other components after the test will be coordinated with the staff of the NEESR award and the staff of the NEES site in accordance to safety regulations.

UNIVERSITY OF MICHIGAN
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

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http://www.engin.umich.edu/dept/cee

March 20, 2009

Dr. Branko Glišić
Department of Civil and Environmental Engineering
Princeton University
Princeton, NJ 08544

Dear Branko:

Thank you for sending me a draft of your proposal "NEESR Payload – Fiber Optic Method for Buried Pipelines Health Assessment after Earthquake-Induced Ground Movement." Our NEES small group award (#0724022) is focused on the development of methods and strategies for monitoring and damage detection of buried pipelines subjected to ground rupture; your payload project nicely matches this focus, and so we are very much interested in your project. We will be able to accommodate your project within our experiments that we have scheduled for June of 2009, 2010, and 2011. We could accommodate your project during any or all of the experiments, though I understand that the timeline for the 2009 test may be a little too close.

We are prepared to accommodate more that one payload project, and I hope that you will be able to secure funds to test the fiber optic method on our concrete pipeline systems, which we will be testing at the NEES Cornell facility.

With best regards,

Radoslaw L. Michalowski
Professor and PI, NEESR SG Project #0724022

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smartec@smartec.ch · www.smartec.ch

# OFFER

Princeton University
Prof. Branko Glisic
E330 Engineering Quad
Princeton, NJ, 08544
USA

**FAX: +1 609-258-2760**

Manno, 13.03.09

**MANDATE: 09-2009 Princeton University US-Instrumentation for testing-DiTeST/MuST**

Your Ref.: e-mail 6 March 09
Our Ref.: AAAQ3848/Esmeralda Mattei

Dear Prof. Glisic,

Thank you for your interest in our monitoring system. We are pleased to submit you the following preliminary and budgetary quote.

| Pos. | Description | Qty | Unit Price | Total Price |
|---|---|---|---|---|
| 1.1 | DiTeSt STA202 Rental, price per week (min. 4 weeks), subject to availability<br>If the client decides to buy the system within 12 months from the start date of the rental, 80% of the paid rental fees will be deducted from the sales price. Buy-out option expires 12 months after the rental start date. | 1 | 3'517.73 USD | 3'517.73 USD |
| 1.2 | DiTeSt STA202 Additional charge for less than 4 weeks rental | 1 | 946.91 USD | 946.91 USD |
| 2.1 | CRACK Detection software - Advanced signal processing for crack detection | 1 | 7'890.88 USD | 7'890.88 USD |
| 2.2 | Rental of CRACK Detection software - Advanced signal processing for crack detection. Price for 1 month rental | 1 | 887.80 USD | 887.80 USD |
| 3 | Rental of DiTeST Dynamic Reading Unit (Prototype). Please confirm with priority your need of this equipment since it is subjected to availability<br>(best case: 3 months before the required starting date for the rental) | 1 | 4'116.98 USD | 4'116.98 USD |

Special Discounts/Conditions:
- -10% Special Princeton University discount on all thepositions/items quoted above
- -100.0% Discount on pos. 1.2 (additional charge for less than 4weeks rental)
- -100.0% Discount on pos. 2.2 (software rental fees)during the rental period of the Reading Unit/s
- - Lease buy-out option on pos. 1.1 and 3 (rental of the ReadingUnits):
  - If the client decides to buy the system within 6 months beginning from the start date of the rental 100% of the paid rental fees will be deducted from the sales price
  - If the client decides to buy the system within 12 months beginning from the start date of the rental 80% of the paid rental fees will be deducted from the sales priceBuy out expires 12 months after the rental start date.

**Conditions:**

Our attached general conditions are binding.

If the exchange rate should exceed 0.91 USD/CHF at the time of invoicing/payment, SMARTEC SA reserves the right to adapt the prices accordingly resp. to ask you to pay the difference.

| | |
|---|---|
| **Prices:** | The prices are in USD, and don't include VAT, delivery costs, packing, import taxes, shipping insurance. |
| **Validity of this offer:** | 3 months |
| **Delivery time:** | 3 months upon receipt of your order. For pos. 1.1; 2.2; 3; upon availability |
| **Delivery terms:** | Ex works Manno - Switzerland |
| **Payment:** | NET 30 days |
| **Warranty:** | 1 year for production defaults |
| **Shipment:** | FedEx or advise |
| **Delivery Address:** | Princeton University<br>Prof. Branko Glisic<br>E330 Engineering Quad<br>Princeton, NJ, 08544<br>USA |

We remain at your disposal for any information you may require

Yours sincerely,

SMARTEC SA

The Director Esmeralda Mattei

Annex: General Conditions SMARTEC SA

Via Pobiette 11, CH-6928 Manno, Switzerland
Phone +41 91 610 1800 · Fax +41 91 610 1801
smartec@smartec.ch · www.smartec.ch

## General conditions of contract for the sale, supply and service of SMARTEC SA products

**1. General conditions**

1.1 These general conditions are binding for all sale, supply and service of SMARTEC SA products. Any conditions stipulated by the customer which are in contradiction to these general conditions shall only be valid if expressly acknowledged by SMARTEC SA in writing.

**2. Prices**

2.1 Unless otherwise agreed upon, all prices shall be deemed to be net ex works SMARTEC SA, excluding Swiss turnover tax, packing and insurances without any deduction whatsoever.

**3. Terms of payment**

3.1 Payments shall be made at SMARTEC SA's domicile, without any deduction for cash discount, expenses, taxes, levies, fees duties and the like, within thirty (30) days of issuance of invoice. SMARTEC SA reserves the right to change the terms of payment if confirmed in writing. Payments shall be deemed complete when SMARTEC SA has full and unlimited access to funds covering the total amount invoiced. Partial deliveries will be invoiced accordingly. Any delay of the supplies or services and notifications of defects does not entitle the customer to any deduction of claims.

3.2 If the customer delays in the agreed terms of payment, it shall be liable, without reminder, for interest with effect from the agreed date on which the payment was due at a rate of 5 percent over the current discount rate of the Swiss National Bank. The right to claim further damages is reserved.

3.3 The material remains property of SMARTEC SA until payment is made in full.

**4. Delivery time**

4.1 The delivery time shall start as soon as the contract is entered into, all official formalities have been completed, payments due with the order have been made, any agreed securities given and the main technical points settled. The delivery time shall be deemed to be observed if by that time SMARTEC SA has sent a notice to the customer informing that the supplies are ready for dispatch.

4.2 SMARTEC SA shall use its reasonable endeavours to deliver the goods by the agreed delivery time and any delay of the supplies or services does not entitle the customer to any right and claims.

4.3 Any delay of the supplies or services does not entitle the customer to rescind the contract or to return the supplies.

4.4 The customer is not entitled to refuse the supply after the issuance of the order confirmation.

4.5 The packing is invoiced at cost price and cannot be taken back.

4.6 Possible damages shall immediately be notified to the shipping company after receipt of the supplies.

**5. Passing of benefit and risk**

5.1 The benefit and the risk of the supplies shall pass to the customer by the date of their leaving the works.

**6. Inspection and taking-over of the supplies**

6.1 As far as being normal practice, SMARTEC SA shall inspect the supplies before dispatch. If the customer requests further testing, this has to be specially agreed upon and paid by the customer.

6.2 The customer shall inspect the supplies and shall without undue delay notify SMARTEC SA in writhing of any defect. The notice shall contain a description of the defect. If the customer fails in doing so, he shall lose his right to have the defect remedied.

6.3 If the client wants to return the material, this has to be specially agreed upon and charges are at the customer expense.

6.4 Deficiencies of any kind in supplies shall not entitle the customer to any rights and claims other than those expressly stipulated in clauses 7 and 8 (guarantee, liability for defects) of the present general conditions.

**7. Guarantee, liability for defects**

7.1 The guarantee period is 12 months. It starts when the supplies are ready to leave the works. If dispatch is delayed due to reasons beyond SMARTEC's control, the guarantee period shall end not later than 18 months after SMARTEC's notification that supplies are ready for dispatch. Items identified as "Prototype" have no guarantee.

7.2 The guarantee expires prematurely if the customer or a third party undertakes inappropriate modifications or repairs or if the customer, in case of a defect, does not immediately take all appropriate steps to mitigate the damage and give SMARTEC SA the possibility of remedying such defect. The defective supplies are to be returned to SMARTEC SA for its inspection. The shipping costs to SMARTEC SA are at customer expense. After the inspection, if the guarantee conditions are satisfied, SMARTEC SA can repair or replace the good. The disposal of good, that cannot be repaired or replaced under guarantee, is at customer expense.

7.3 Excluded from SMARTEC's guarantee and liability for defects are all deficiencies that cannot be proved to have their origin in bad materials, faulty design or poor workmanship, like for example incorrect handling during the installation.

**8. Exclusion of further liability**

8.1 All cases of breach of contract and the relevant consequences as well as all rights and claims on the part or the customer, irrespective on what ground they are based, are exhaustively covered by these general conditions of supply. In particular, any claims not expressly mentioned for damages, reduction of price, termination of or withdrawals from the contract are excluded. In no case whatsoever shall the customer be entitled to claim damages other than compensation for costs of remedying defects in the supplies. This in particular refers, but shall not be limited to, loss of production, loss of use, loss of orders, loss of profit and other direct or indirect or consequential damage.

**9. Re-export and security**

9.1 The buyer is responsible for compliance with all domestic and foreign export regulations. The buyer shall be responsible to compliance with all regulations and shall further pass such responsibility to all subsequent third parties.

**10. Loaned Material**

10.1 The buyer shall be held accountable for the maintenance and protection of loaned materials or tools and for damages incurred during the time that they are in his possession.

10.2 The loaned material remains the property of SMARTEC SA.

**11. Services**

11.1 SMARTEC SA can offer services such as installation- and measurement support. Unless otherwise agreed upon, the client is responsible for the installation and the measurement.

11.2 SMARTEC SA can provide support to define a monitoring strategy. Proposals proceeded with in collaboration with SMARTEC SA are based on information provided by the client, which is not verified, and on SMARTEC's experience. Service consultancy, which has not been verified by an engineer, is only a recommendation. A possible deficiency due to faulty measurements or missing measurements, such us misinterpretation of the obtained measurements does not entitle the customer to any rights and claims.

**12. Jurisdiction and applicable law**

12.1 The place of fulfilment shall be at the registered office of SMARTEC SA, 6928 Manno, Switzerland.

12.2 Swiss substantive law shall govern the contract.