Seismic Monitoring & Response for The Trans-Alaska Pipeline System

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Abstract

The 800-mile Trans-Alaska Pipeline System (TAPS) passes through extremely remote regions, where there is a high potential for seismic activity. Alyeska Pipeline Service Company, the TAPS operator, has been on the forefront of seismic engineering and situational awareness, and continues to enhance its capabilities. TAPS has used earthquake monitoring since the pipeline was constructed in 1977 and recently upgraded to a fourth generation of its monitoring system. This upgrade includes recent technology to improve accuracy and increase system redundancy, and it incorporates lessons learned during the 2018 M6.3 Kaktovik and the 2018 M7.1 Anchorage earthquakes. The modernized earthquake monitoring system includes strong-motion accelerograph stations installed at key locations along the pipeline tied into the control system to provide real-time detection of seismic events. The accelerometers also telemeter data to provide local constraints in ShakeMap that in addition to providing site-specific shaking values, they openly to constraining ground motions elsewhere so shaking at locations without stations can be better inferred. Alyeska then employs U.S. Geological Survey's ShakeCast system to automatically ingest the ShakeMap to provide near real-time alerts of shaking as well as inspection priorities across the system, both for pipeline assets and infrastructure. TAPS stakeholders who receive ShakeCast alerts via email and text messages include controllers, engineers, and emergency managers. As part of our standard post-earthquake protocol, damage assessment checklists have been pre-deployed at multiple locations to guide these teams as they determine the integrity of TAPS following an event. This unprecedented level of situational awareness allows for rapid prioritization and deployment of damage assessment teams. The purpose of this manuscript is to expand on the details of these systems.

Keywords: Infrastructure; Lifeline; Earthquake Response; Pipelines; ShakeCast, ShakeMap; Emergency Planning

1. Introduction

The Trans-Alaska Pipeline System (TAPS) consists of a 48-inch crude-oil transportation line spanning 800 miles from the oil fields in northern Alaska to the ice-free port of Valdez, passing through regions of extreme remoteness and high seismic risk. Seismic monitoring and response planning for a system distributed over hundreds of miles is a substantial challenge and is critical to ensuring the system is safe and environmentally responsible.

Designed and constructed in the 1970s, TAPS was built to withstand earthquake loads without structural collapse or release of crude oil [1]. As additional protection, an Earthquake Monitoring System (EMS) was installed consisting of remote strong-motion accelerograph stations. This system has undergone several design iterations over the life of the pipeline with the most recent fourth-generation upgrade going online in spring of 2019.

Today's EMS is maintained by Alyeska Pipeline Service Company (APSC), the TAPS Operator, and comprises three systems working together to provide rapid information on seismic events occurring near the pipeline. Shown in Fig. 1, these systems include the seismic monitoring stations, the earthquake alarm tie-in at the Operations Control Center (OCC), and the Earthquake Response Management System (EQRMS). The OCC is the central control room for TAPS and is manned 24/7 by controllers responsible for monitoring and operating the pipeline system.

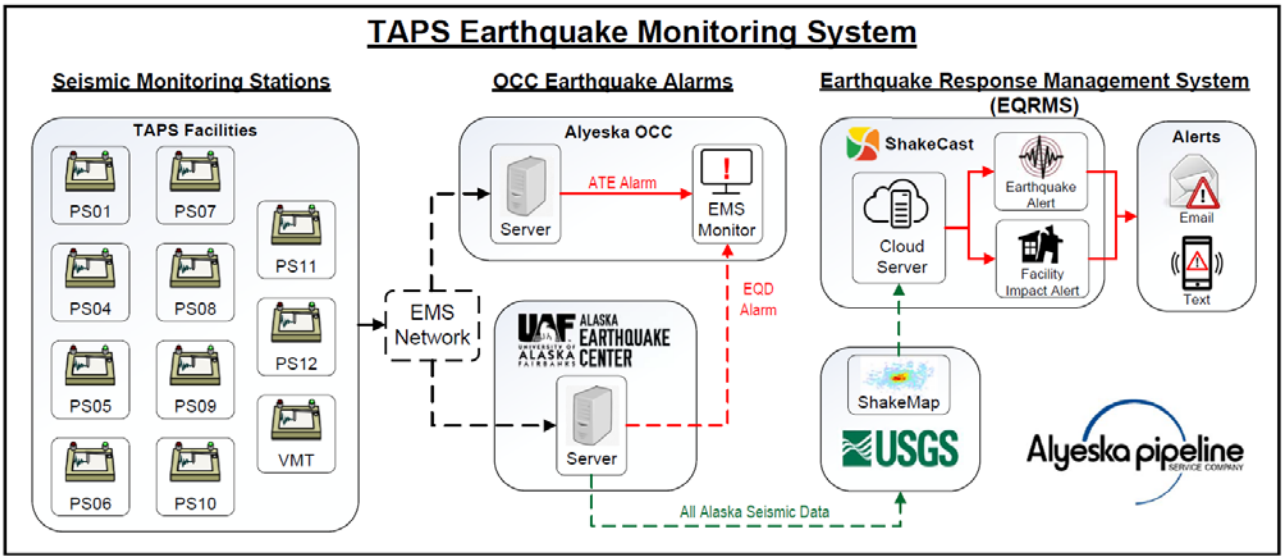

Fig. 1 – Flow of seismic information and notifications for the TAPS earthquake monitoring system (EMS).

2. Background

The EMS has been an integral part of the pipeline control system since the beginning of pipeline operation in 1977. Seismic monitoring stations were deployed at 11 facility locations along the pipeline: Pump Station 1, Pump Stations 4 through 12, and the Valdez Marine Terminal.

The seismic monitoring stations initially deployed were strong-motion instruments fabricated as a custom system in 1976 by Sundstrand Data Control, Redmond, Washington, in accordance with Alyeska-specified performance requirements. The 11 remote stations were configured with Intel 8080 microprocessors for real-time computational capability and linked to the pipeline control system computer at the TAPS OCC over a single telecommunications channel. The central control system computer processed seismic event data provided by the EMS to evaluate the severity of ground shaking along the pipeline route and to assess the potential for damage to the pipeline and supporting facilities. This information was only available at the OCC [2].

After 21 years of service, the EMS was upgraded with second-generation hardware. New seismic monitoring stations were installed at the same locations as the original system and a PC-based monitoring system was installed at each site enabling onsite data processing and TCP/IP-based network sharing between the stations and the OCC. This allowed for seismic event reports to be available at each individual station, rapidly improving the event response time [3].

The EMS was put to the test in 2002 when the design-level M7.9 Denali earthquake struck Alaska. The system fulfilled a vital role by providing real-time event alarms, recording ground motions and generating a detailed assessment and inspection checklist. Repairs were completed and the pipeline returned to operation after a total downtime of 66 hours [4].

In 2008, the third-generation upgrade of the EMS saw the seismic monitoring stations replaced with commercial, off-the-shelf, strong-motion instruments. Through a partnership with the Alaska Earthquake Center (AEC), broadband instruments were also installed at each location. All sensors were incorporated into the regional seismic monitoring network maintained by the AEC. An additional improvement was the introduction of the EQRMS. This custom software solution compared an event ShakeMap [5] generated by the AEC against a TAPS facility database to determine if there was potential for damage. Event-specific checklists would then be generated to assist with post-earthquake damage assessment [6].

In 2019, the most recent update to the EMS went online, featuring improvements to the servers processing seismic data, a new version of the EQRMS based on ShakeCast, and updates to the earthquake response procedure.

3. TAPS Earthquake Monitoring System

The EMS employs multiple integrated systems to monitor and respond to earthquake activity near TAPS as shown in Fig. 1. This enhances the ability of APSC to safely operate the pipeline in the challenging Alaskan environment.

The first stage in the EMS process is a network of seismic monitoring stations which constantly monitor ground motion for signs of an earthquake. This constant flow of data is transmitted over a dedicated EMS network to redundant servers at the TAPS OCC in Anchorage, Alaska, and the AEC in Fairbanks, Alaska.

When seismic activity is detected, the ground motion data are analyzed by scientific software to determine the peak ground acceleration experienced at TAPS facilities. If movement is determined to exceed a predetermined threshold, an earthquake alarm is issued to the pipeline controllers at the OCC, alerting them to a potential earthquake. All of this occurs within seconds of ground motion being detected. The pipeline controllers are then well informed about the intensity of shaking along the pipeline and can make decisions on how to respond. In the case of a potentially damaging earthquake, pipeline controllers will increase monitoring on the impacted sections of TAPS and be prepared to shut down if anomalies are detected.

Data from the EMS along with regional sensor data are also used to automatically contribute to a ShakeMap for the event. The EQRMS utilizes ShakeCast to monitor the U.S. Geological Survey (USGS) earthquake product feeds for ShakeMaps and automatically generates an alert for events located near TAPS. ShakeCast is an open-source, post-earthquake situational awareness application that automatically retrieves earthquake shaking estimates from ShakeMap, compares intensity measures against users' facilities, and generates potential damage assessment notifications [7].

This alert is typically issued within 5 minutes of an event and is distributed to APSC stakeholders by email and text messaging. In addition, the EQRMS employs the USGS ShakeMap shaking estimates by comparing them to a fragility database of TAPS assets geo-located with latitude and longitude information. This allows the system to estimate if and where damage may have occurred to TAPS facilities and equipment. When it determines there is a potential for damage, the EQRMS issues a second alert including a list of equipment and locations with an estimate for potential damage.

These data from the EQRMS are then used to guide any field response effort. Damage assessment teams can be deployed to the area with the greatest risk for earthquake damage and then work their way to lower risk areas. These teams will use post-earthquake damage evaluation checklists which are pre-deployed to TAPS facilities.

4. Seismic Monitoring Stations

The EMS seismic monitoring station network is a system of 11 Digital Strong Motion Accelerograph (DSMA) stations feeding into to a dedicated EMS communication network. This system of DSMA stations provide real-time data on ground motions experienced at TAPS facilities.

The DSMA stations are installed at 11 locations along the 800 miles of TAPS: Pump Station 1, Pumps Stations 4 through 12, and the Valdez Marine Terminal. These locations were selected when the original EMS was developed in 1977 to provide reasonable coverage along the route for detection of ground motion associated with strong earthquakes and pursuant to the availability of power and network communications. Some pump stations are no longer active but continue to house control system components and communication systems, including the seismic monitoring stations.

The DSMAs are shallow borehole accelerometers manufactured by Kinemetrics and designated as the Model 10560-18 EpiSensor. The accelerometers are installed in a 5-foot deep borehole in a 4-inch diameter Schedule 40 PVC casing. To minimize the effect of structural vibration feedback or equipment vibration, the accelerometers are installed at a minimum clear distance from buildings equal to the largest plan dimension of the building.

The accelerometers are connected by cable to a wellhead junction box and then onward to a Kinemetrics Q330 digitizer that is mounted in a rack located within the communications building at each site. A dedicated network transmits all communications from the station digitizers to the OCC in Anchorage, Alaska, and the AEC in Fairbanks, Alaska. The basic data from the seismic monitoring stations are the three components (two horizontal and one vertical) of ground acceleration measured as a digital time series with sufficient sample rate and bandwidth to capture motions of engineering interest, from 0-50 Hz in frequency and from 0.001 to 2g peak acceleration.

The AEC has also installed broadband seismometers alongside the DSMAs to provide additional data that are key to the determination of earthquake epicenter, location, and magnitude. While not a direct component of the TAPS EMS, data from the broadband seismometers and other similar instruments in the AEC network enhance the accuracy of earthquake reporting to TAPS and also contribute significantly to basic earthquake science in Alaska.

The seismic monitoring station instruments are designed to monitor ground motions and record and analyze data when strong ground shaking is detected. Because earthquakes are infrequent, the stations are designed to operate for many years with minimal human interaction. Routine system health monitoring, system checks, and diagnostics are administered remotely through the EMS network by AEC personnel. Preventive maintenance of field hardware is performed annually by the AEC and as needed in the case of malfunction.

5. Operations Control Center Alarms

Data from the seismic monitoring station network are used to provide real-time alarms at the OCC to alert the TAPS controllers that an earthquake may have taken place. The earthquake alarms are displayed alongside the TAPS control system delivering real-time situational awareness to the controllers.

Redundant servers located at the OCC and at the AEC are responsible for acquiring and processing seismic data to determine when an alarm should be issued. These systems continuously monitor ground acceleration data streams from the seismic monitoring stations. When measured ground accelerations exceed preset thresholds, an Acceleration Threshold Exceedance (ATE) alarm is automatically transmitted to the OCC. The ATE alarms would be the first evidence of earthquake activity received by the OCC.

Due to their automated nature, ATE alarms can be triggered by non-seismic activity such as heavy equipment or snowplows operating in the vicinity of a seismic monitoring station. To confirm whether a seismic event has occurred, a second EarthQuake Detection (EQD) alarm is issued once more data are available. EQD alarms are generated by the AEC when earthquake event parameters for new events within the Alaska seismic network meet predefined criteria for location and magnitude. Automated systems at the AEC evaluate data received from stations across its seismic network, which include the strong-motion and broadband instruments at TAPS locations as well as stations across the state of Alaska. EQD alarms can also provide notification of seismic events which may have occurred between seismic monitoring stations and did not trigger an ATE alarm. EQD alarms are generally received within 5 minutes of the event.

Between the immediate ATE alarm and the confirmation EQD alarm, the TAPS controllers contact field personnel for damage reports and continue monitoring the control system for operational upsets. While seismic alarms are critical for situational awareness, they are considered secondary to other alarms and data from pipeline control and monitoring systems. TAPS is not shutdown based solely on seismic alarms. Instead, the pipeline controller takes the seismic event into account while observing other instruments to determine if immediate control actions are required.

6. Earthquake Response Management System

The EQRMS provides rapid information to the APSC on seismic events and the potential for damage to TAPS. This information is used to guide post-earthquake damage assessment teams as they inspect the pipeline and associated infrastructure. These inspections are critical for identifying and repairing damage in order to restore TAPS to operation.

EQRMS uses the USGS ShakeCast software to monitor for earthquakes occurring near TAPS. The ShakeMaps used in ShakeCast are generated using seismic data from the 140+ seismic sensors operated by the AEC in addition to the TAPS seismic stations. This provides system redundancy where the EQRMS can continue to operate even if the TAPS network is damaged.

6.1 EQRMS Alerts

Using ShakeCast, the EQRMS is configured to automatically issue two types of alerts following a seismic event: Earthquake Alerts and Facility Impact Alerts. These are issued via email and text message to TAPS stakeholders including controllers, operators, emergency response, engineers, and managers.

Earthquake Alerts are issued when a seismic event has been detected near the pipeline based on preset magnitude and location criteria. The alert is typically issued between 3–8 minutes after the actual event has taken place.

Hundreds of earthquakes occur in proximity to TAPS each year. Most are small magnitude events, not noticeable to humans, but detectable by instruments. The objective of the EQRMS is to detect events that are of possible engineering significance to TAPS, i.e., potentially compromising functional integrity and safety, as well as events that can be felt by people in the general vicinity of the pipeline route. In the latter case, the availability of authoritative information on small, but noticeable, events provides reassurance that all earthquakes in proximity to TAPS have been detected and evaluated. Thus, for the sake of completeness and prudency, the EQRMS detects and reports a far greater number of minor events than larger events that might prove to be of concern.

Earthquake Alert messages include basic information on the magnitude, location, and time of the event. An example email alert is shown in Fig. 2. If ShakeCast determines that there is a potential for damage to TAPS facilities, then a Facility Impact Alert will follow the Earthquake Alert. Facility Impact Alerts are intended to rapidly notify APSC operations when an earthquake has the potential for damaging TAPS and where this damage is most likely. This information is then used to guide any field inspection response by flagging facilities for inspection and prioritizing those most likely damaged. This alert would be issued within 10-15 minutes of the actual seismic event taking place.

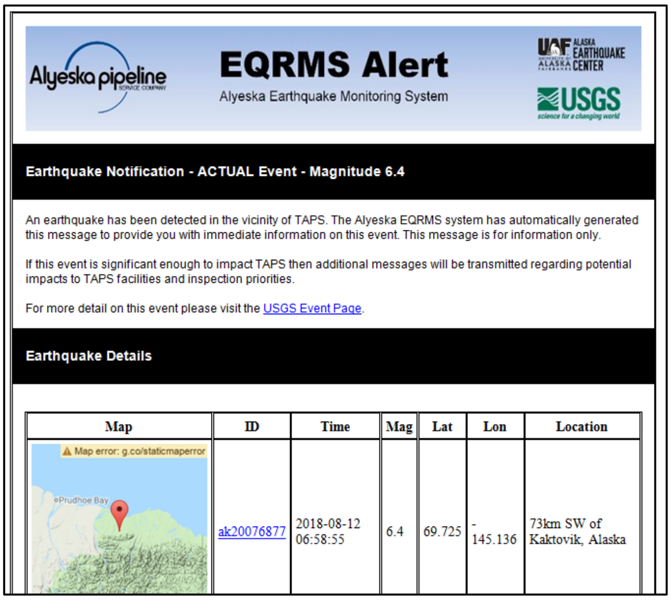

Fig. 2 - Example earthquake alert email message

Facility Impact Alerts are also sent out via email and include an intensity ShakeMap for the event and a list of facilities impacted and the probability of damage. An Excel file is also included as an attachment to aid in sorting and filtering the list of impacted facilities as this could include hundreds of entities. An example Facility Impact email alert is shown in Fig. 3. A text message alert is also issued to directly alert the recipients of to the potential for damage and direcs them to check the email message.

In addition to the email and text message notifications, all alerts are posted to an internal SharePoint site of APSC. This allows for individuals not on the alert distribution list to see alerts and check for the latest updates.

6.2 Facility Database

ShakeCast is able to determine the potential for damage based on a facility database including all TAPS assets and the expected fragility of each. This is compared to the predicted ground motion parameters found in the ShakeMap at each facility's location.

The EQRMS Facility Database includes entries for TAPS assets located along the pipeline corridor as well as urban support areas. Each database entry contains the name and type of the asset, location information in the form of latitude and longitude, and the facility fragility parameters. Facility types are broken down into categories as shown in Table 1.

Large TAPS facilities such as pump stations and the marine terminal in Valdez are included in the facility database as single entities instead of including each structure within the facility. This was done because it was recognized that if an entire facility experienced significant ground motion, then all assets should be inspected. This greatly simplifies the facility database as there are hundreds of individual structures that are not required to be individually tracked. Even with this

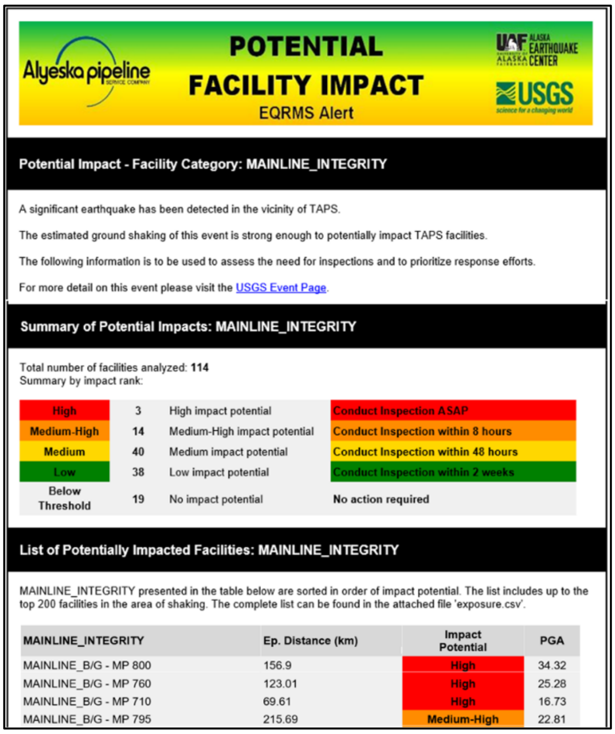

Fig. 3 - Example facility impact alert email.

simplification, the TAPS facility database tracks over 490 individual entries.

Table 1 – Facility Types

Facility Type	Description
FACILITY	Includes pump stations, airports, metering facilities, urban offices, and control centers. Each facility may include multiple fragility parameters such as Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) to account for damage to different types of structures; or they may include a single parameter such as Modified Mercalli Intensity (MMI).
MAINLINE_ INTEGRITY	Includes the mainline pipe, valves and long-span river crossings. The mainline pipe is included in the database as a series of points at 5-mile intervals. Each interval is classified as above ground or below ground.
GEOHAZARD	Includes geotechnical hazards which could threaten the mainline such as landslide areas, slope instabilities, and fault crossings.
COM_SITE	Includes all remote microwave communications sites along TAPS.
BRIDGES	Includes all pipeline and right-of-way vehicle access bridges.

6.3 Fragilities

The facility fragility parameters are the threshold values set in the facility database and are used by ShakeCast to judge if an asset has potentially been damaged based on the estimated ground motion. TAPS defines these parameters as distinct percentages of the design seismic loads used in the original design.

While the ShakeCast system is able to produce a detailed analysis to determine the fragility of individual structures, TAPS elected to use a conservative approach, linking seismic design criteria to fragility. This was done because TAPS takes a very conservative approach to pipeline safety and will typically perform a precautionary inspection regardless of what the data show. The EQRMS accounts for this by focusing on broad data to prioritize inspections instead of improving the accuracy of individual facility predictions.

Fig.4 and Table 2 reflect the seismic design criteria used in the original design of TAPS in the 1970s. Table 3 provides the percentage of the seismic design criteria used in ShakeCast for the facility fragility thresholds.

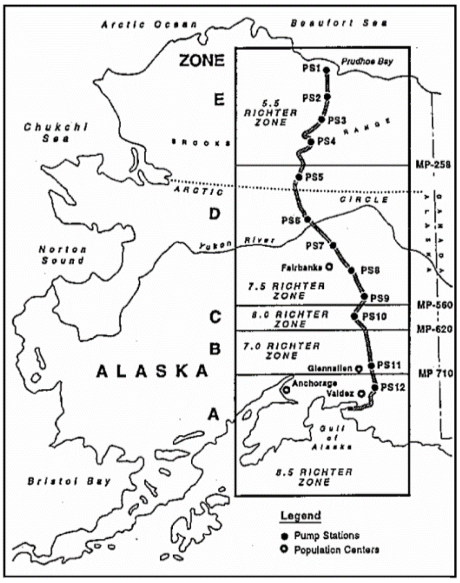

Fig. 4 – TAPS seismic design zones.

Table 2 –Seismic design parameters by zone

Zone	MP	PGA (%g)	PGV (cm/s)
5.5 Zone	0 - 258	10	5
7.0 Zone	620 - 710	15	7
7.5 Zone	258 - 560	22	11
8.0 Zone	560 - 620	33	16
8.5 Zone	710 - 800	33	16

Table 3 –Facility fragility as % of seismic design load

	Grey	Green	Yellow	Orange	Red
5.5 Zone	25%	50%	100%	150%	200%
7.0 Zone	15%	30%	60%	120%	175%
7.5 Zone	15%	30%	60%	120%	175%
8.0 Zone	13%	25%	50%	100%	150%
8.5 Zone	13%	25%	50%	100%	150%

Note that the percentages used vary by seismic design zone. In zones of lower seismicity, a higher percentage of the design ground motion is used for the fragility, since the lower ground motions in these regions are significantly less likely to result in damage as compared to the high seismic zones. In addition, much of the equipment installed on the pipeline was designed for the higher seismic zones and then installed everywhere for consistency.

7. Post-Earthquake Damage Assessment

Following a significant seismic event, post-earthquake damage assessment inspections will be conducted based on the guidance of the EQRMS and the judgment of onsite personnel. TAPS inspection procedures are based on *ATC-20: Procedures for Post-earthquake Safety Evaluation of Buildings* [8]. Following this standard, a rapid evaluation is completed as soon as possible followed by a detailed evaluation where necessary.

A typical ATC-20 damage assessment procedure uses generic damage documentation forms to allow for a wide variety of unknown building types. TAPS has the advantage of already knowing the construction type and critical systems housed within the buidings along the pipeline. Therefore, damage assessment checklists have been generated and pre-deployed to each TAPS facility and are also available on an accessible network drive (Fig. 5).

Using these customized checklists has several advantages over the generic ATC-20 forms. They speed up the damage assessment process because the forms help organize the inspection of multiple structures on a single site and ensure that none are missed. Finally, they give the opportunity to single out critical systems within individual structures that require more careful inspection.

Post-Earthquake Field Review Checklist
TAPS Pump Station 13

Name(s) of Field Reviewers: ______________________ Date: __________

Post-Earthquake Rapid Damage Assessment Procedure:

General Directions:
- Consider personal safety first! **Do not put yourself in a position of risk**
- If there is any risk of building collapse, await emergency personal for assistance
- Be alert for aftershocks. They may be strong enough to cause additional damage.

Prior to Entry:
- Walk around exterior of building looking for damage
- Work through checklists for 'Prior to Entry' answering each question 'YES' or 'NO'
- If 'YES' to any question, **DO NOT ENTER BUILDING**. Consult with security for next steps.
- If 'NO' to all questions, enter building and continue assessment

Inside Building:
- Walk through all accessible areas
- If you smell gas or are see evidence of structural collapse, **IMMEDIATELY EXIT BUILDING**
- Work through checklists for 'Inside Building' answering each question 'YES' or 'NO'
- If 'YES' to any questions, consult with security on next steps:
  - Building access may be limited to short visits
  - Cordoned off damaged portions of building
- If 'NO' to all questions, building can be re-occupied

Inspection Priorities:
- Tier I — Life-Safety/Pipeline Operation
- Tier II — Pipeline Maintenance
- Tier III — Other Facilities

			Rapid Post-Earthquake Damage Assessment										
			Prior to Entry			Inside Building							
Priority	Location	Building Name	Explosive Vapors: Do you Smell/See/Hear Gas or Vapors Leaks?	Building Structure: Any Sign of Obvious Damage?	Emergency Exits: Are Stairs/Doors/Hallways blocked or damaged?	Explosive Vapors: Do you Smell/See/Hear Gas or Vapors Leaks?	Overhead Items: Has overhead equipment/ceiling tiles fallen down? Is anything leaking?	Equipment: Is there obvious damage to equipment? Is it a hazard?	Piping: Is there damage to piping systems? Is anything leaking?	Doors/Windows: Are doors jammed? Are windows broken?	Debris: Is debris blocking access to any areas? Is there broken glass?	Bathrooms: Are bathroom facilities damaged? Is anything leaking?	Emergency Exits: Is anything blocking the path of egress to emergency exits?
Tier I	Varies	ABOVE GROUND STATION PIPING											
Tier I	Varies	EXTERIOR CABLE TRAY AND SUPPORTS											
Tier III	1	PERMANENT LIVING QUARTERS											
Tier II	2	WATER MIST MODULE											
Tier III	4	FLAMMABLE LIQUIDS BUILDING OUT-OF-SERVICE											
Tier I	8	COMMUNICATIONS MODULE											
Tier I	9	MICROWAVE TOWER											
Tier III	10	GUARD BUILDING											
Tier III	11	TRUCK LOADING BUILDING											
Tier II	12	SHOP /WAREHOUSE BUILDING											

Fig. 5 - Example post-earthquake rapid evaluation checklist.

The first step in the process is the rapid evaluation, completed immediately following the earthquake by the onsite personnel stationed at the facility. This team will be a mix of technicians, site engineers, and security personnel who are intimately familiar with the facility and its operation. Results from the rapid evaluation are reported back to a centralized Incident Management Team (IMT). An example of a TAPS rapid evaluation checklist is shown in Fig. 5. This typically requires 5–15 minutes per structure and is focused on checking the life-safety of the building and identifying obvious areas of damage. At the conclusion of this assessment, the building is tagged with a green, yellow, or red placard following the ATC-20 procedure.

A detailed evaluation is completed hours or days after the earthquake. These require 1–4 hours per building and are a thorough examination of the building structure along with the systems and components operating within the building. Unlike the ATC-20 method, a detailed evaluation will be completed for most if not all structures at a site. This is due to the critical nature of the systems installed within TAPS facilities. Minor damage may not be immediately apparent, which could be of great consequence if not found and corrected. This requires a thorough inspection of each facility with a focus on process safety.

Detailed evaluations are carried out by multidisciplinary teams of engineers. By following the detailed evaluation checklist, this team will complete a thorough investigation of each building and critical system. Results from the detailed evaluation are reported to the centralized IMT. An example of a TAPS detailed evaluation checklist is shown in Fig. 6.

Post-Earthquake Field Review Checklist
TAPS Pump Station 13

Name(s) of Field Reviewers: ____________________ Date: __________

Cell Legend:
- ☐ Enter ✓, D, or SR
- ☐ Not applicable, no entry

Fill Unshaded Cells With:
- ✓ OK, no damage and/or functional
- D Unsafe, unsatisfactory, damaged, loss of function
- SR Potential damage, Specialist Review required

Inspection Priorities:
- Tier-1 Life-Safety/Pipeline Operation
- Tier-2 Pipeline Maintenance
- Tier-3 Other Facilities

Detailed Post-Earthquake Damage Assessment

Tier	Item	Safe Entry Atmosphere (Explosion, Breathing)	Safe Egress Paths (Doors, Stairs, Ladders)	Foundation Integrity & Restraint; Sliding	Structural Integrity or Enclosure/Rack Integrity	Anchorage/Restraint or Support Integrity	Pounding, Displacement, Loss of Alignment	Cable Integrity (Drops, Terminations, Expansion Joints. & Ground Pen.)	Operational Function-ality or Readiness	Leakage & Spray, Primary Containment	Piping/Tanks - Dents, Gouges, Wrinkles	Secondary Containment Integrity
Tier I	ABOVE GROUND STATION PIPING										Facility location:	Varies
	a. North of hallway											
	b. South of hallway											
	c. East of main pump building											
	d. Pipe rack running out to flare stack											
	e. Other											
	Notes:											
Tier I	EXTERIOR CABLE TRAY AND SUPPORTS										Facility location:	Varies
	Structures, cable tray, & cabling, esp. at transitions and tray joints:											
	a. Generator module & surrounding area											
	b. South of main pump building toward tank farm											
	e. Other											
	Notes:											
Tier III	PERMANENT LIVING QUARTERS										Facility location:	1
	a. Building shell & foundation											
	b. Stored materials											
	c. Fire detection and suppression system											
	d. Plumbing and piping											
	e. Overhead lighting, heating & ventilating systems & ductwork, etc.											
	Notes:											

Fig. 6 - Example post-earthquake detailed evaluation checklist.

7.1 Training

TAPS conducts regular training sessions for internal personnel to ensure a high level of earthquake preparedness. All training is conducted as a combination of classroom instruction and field exercises. Classroom instruction uses ATC-20 based resources to prepare individuals for damage assessment activities, immediately followed by a field exercise at a live TAPS facility where the students complete a simulated post-earthquake damage assessment following the evaluation checklists.

Earthquake response training is divided into two sessions: one for non-technical individuals completing the rapid evaluations and one for the engineers expected to complete the detailed evaluations. A one-day training session is offered to prepare individuals to perform rapid evaluation. This session is designed for technicians, operators, and security and other non-engineering personnel who work at TAPS facilities and would likely be onsite immediately following an event. This course is broken into a 4-hour classroom session with a primer on ATC-20 and then a 4-hour field exercise to practice completing a rapid evaluation.

The second course is a two-day session, designed to prepare engineers for rapid and detailed evaluations. One day is spent in the classroom going through the Safety Assessment Program (SAP) Evaluator training program as developed by the California Office of Emergency Services. The SAP training program is used since engineers completing the training are registered with the California program which tracks refresher training requirements. Day two of the engineer training reviews the TAPS procedures for damage assessment and then launches into field exercises.

In both classes, the field exercises are critical for reinforcing the classroom learning and giving a brief experience of what it is like to assess an operational process facility. The students are typically dividedinto teams of three to five individuals, assigned areas, and then sent to work through the evaluation checklists. ‘Simulated damage’ placards have been placed in each facility to give the teams something to look for.

8. Lessons Learned from Recent Events

In 2018, Alaska experienced several significant seismic events. After 15 years without an earthquake impacting TAPS, two events within four months triggered responses of the EQRMS. Fortunately, neither event resulted in any damage to TAPS; however, they proved invaluable in testing our procedures and highlighting areas needing improvement.

8.1 M6.4 Kaktovik Earthquake

The magnitude 6.4 Kaktovik earthquake occurred on Sunday, August 12, at 6:58 am on the North Slope of Alaska. The event was centered in the Sadlerochit Mountains approximately 80 miles east of TAPS Pump Station 2. The magnitude of this event was surprising as previous studies had estimated this region capable of producing a maximum of a mid-five magnitude earthquake.

While shaking was felt along a 100-mile stretch of TAPS, measured ground motions were low and the EQRMS did not predict any damage to TAPS facilities. As a precaution, TAPS field personnel immediately conducted facility checks and started a ground survey of the pipeline right-of-way. By the end of the day, over 100 miles of ground had been covered and no earthquake-induced damage was observed. Two days later, an engineering team arrived and conducted a detailed evaluation of critical structures and systems at several pump stations. No earthquake damage was discovered, and no further action was required.

The EMS was midway through an upgrade when this event occurred, and the event served as a test run for many of the concepts being developed. Lessons learned from this event included the following:

- A detailed evaluation of a large industrial building containing many valves, pumps, and safety systems takes much longer to complete than expected.
- The large number of aftershocks following the main event resulted in an excessive number of automatic alerts. This was addressed by eliminating ‘update’ alerts which were being issued as magnitudes were updated.

- Field personnel had to locate checklists on the network server and print hardcopies before they could be used. Preprinted forms are now available at all field locations to eliminate reliance on networks and power.

8.2 M7.1 Anchorage Earthquake

The magnitude 7.1 Anchorage earthquake occurred at 8:29 am (AKST) on Friday, November 30th, and was the largest magnitude earthquake to strike a U.S. urban area in 15 years. The epicenter was 9 miles northwest of downtown Anchorage, Alaska, and resulted in widespread damage but no fatalities.

This event was located 120 miles from the TAPS right-of-way, and the EQRMS did not predict a potential for damage. As a precaution, the pipeline was shutdown while facilities were inspected, and an air/ground surveillance operation was initiated along the right-of-way. The line was restarted within 7 hours once it was confirmed to be undamaged.

A greater impact was realized at the TAPS corporate headquarters located in Anchorage where severe ground shaking was felt. While there was only minor damage to the facilities, there was a substantial social disruption to the workforce as individuals dealt with damage to their personal property and local schools were temporary closed. This resulted in business disruptions which had not been envisioned in TAPS' previous response planning.

This event highlighted for TAPS that contingency planning tended to focus primarily on the pipeline and associated systems. Plans had not considered a scenario where TAPS corporate offices were impacted while the pipeline was unaffected. Specific lessons learned by TAPS from this event included the following:

- An automated system was implemented to contact all TAPS personnel to conduct welfare checks and distribute information.
- The EQRMS was updated to include non-process facilities in Anchorage and elsewhere. This provides an improved picture of the impact to the overall company following an earthquake.
- Detailed evaluation checklists were found to be too involved to support quick building evaluations. This led to the development of the rapid evaluation checklists.

9. Conclusion

TAPS successfully operates a world-class pipeline system in a challenging seismic environment thanks in large part to its EMS. The EMS, combined with forward-thinking seismic design, has resulted in over 40 years of operation without a single spill resulting from an earthquake event, despite experiencing significant shaking and ground displacements. Recent updates to the EQRMS that incorporates ShakeCast provides TAPS operators with unprecedented levels of situational awareness and response capabilities following seismic events.

To the authors' knowledge, TAPS is the first oil and gas pipeline system to implement a comprehensive earthquake monitoring system as described in this document. With technological advances such as the USGS ShakeMap and ShakeCast software and commercially available seismic sensors, the barriers are becoming lower for any infrastructure owner to implement a similar system.

The following recommendations are advanced for others considering implementing an earthquake monitoring program to protect their assets:

1. ShakeCast is an excellent tool for monitoring a geographically distributed system of infrastructure. It provides a great deal of functionality in an efficient open-source software package.
2. Installing strong-motion sensors is not necessary for many systems. They should only be considered where immediate control action can be taken to react to the event (e.g., pipelines, power systems).
3. Build a relationship with the operators of your regional seismic network. They are valuable partners in planning and responding to significant events.

4. Earthquake monitoring is not a substitute for good design. Ensure your infrastructure is properly engineered to resist anticipated earthquake loads.

10. Acknowledgements

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11. Disclaimer

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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