PROTECTION OF SUBSEA INFRASTRUCTURE IN ICE ENVIRONMENTS

KENTON P. PIKE

by

Thisthesisbcginswilhan oullookoflheoffshoreewfoundland oiland gas induslry While hydrocarbon resources are plentiful. adverse opcrating conditions and risk of impaci from encroaching icebergs leads to challenges in design. projecl execution and opcration.Acceptable risklevelsregarding hydrocarbon rclease lo lhecnvironmenlhave to be mCI by providing sufficienl proleclion for vulnerJble asselS. A discussion on the parametcrsinvo!ved in detemliningconlact risk bclwecn Ihckcel of an icebcrg and a

For subsea struclures. many protection concepls have bccn considercd forapplicalion in

sclectedconcept for major field devclopmenl and produclion schemesonlhcGrand

lhat onlyrequirc limitedsubsea infrastruclurc. Otherprotcclion concepts which have

The Pl'otection of subsea installations required for subsca tic-b:lCkdcvclopmentsvia tubularframc prolcction structures is proposed in thc prcsent study. Thrccdiffcrcnt gcomctric configurations are analyzed. The first configuration consisls of a rectangular

struClurc has a large circular basc and a smaller circular top ponion. with lhc top and basc conncclcdusingslraightinclined mcmbcrs.togivclhcappcaranccofalruncatcdconical structural response of the frames subjcctcd to icc loading. Primaryfailuremechanisms during ice·subsea structure imeraction are assessed using an energyapproach.Dcsign loads are estimated using a simple ice load model accounting for crushing failure of thc

Progress in this research area should involvcsimulutionofa wider range of icc contact cvcnts. ltissuggestcd thatthcfiniteelementmodelbcimprovedtowardcontinuum

substructurcmodelcd using kinematic constraints representing iceberg size and stability

guidance and limed uring the complclion of lhis project in its entirCly. I would also likc 10 exprcss gratitude to Paul Sluckey. Freeman Ralph. and Tony King of C-CORE for

programming knowledge. I thank them both. Also I would like to thank C-CORE for providing me with a space to work. access to software and various reports. and rcscarch

questions, MITACS (www.mitacs.ca) granted mean intcrnship scholarship, for that I

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LIST OF SYMBOLS

C_{NET}	Net incremental system cost
C_{CAPEX}	Incremental capex cost
C_{RISK}	Cost of risk from icebergs
	Equipmentrepair/replacementcost
	Environmental and equipmenl cleanup cost
	Heighl ofsubseafacilityabovescabcd
	lcebcrgdraft
	Waterlinelcnglh oficeberg
	Annual contact frequency belween scouring icebergs and subsea facilitics
	Proportion of icebergs wilh draft capable of contacling subsea facility
$\overline{W}_{fk}$	Mean width offrcc-noating keels
D_f	Effeclive diameter of subsea facility

Normal force at iceberg keel

Horizontal force at iceberg keel

Vertical force at iceberg keel

Slope angle or structure face

$M_{righting}$	Righting moment of iceberg

$\overline{KG}$	Distance from keel to center of gravity
I_{wp}	Waterplane momenl of incrtia
$\overline{q}_{vp}$	Ultimate vertical bearing resistance of soil

expccled 10 plateau wilhin thenexl few years meaning new assets need tobcexploiledlo mainlain full producHoncapacity. Marginal fieldde\lelopmenl hasacled as a calalysl

The present sludy begins by reviewing IhecUrrell1 slate oflhe offshore ewfoundland

prodUClionisdcclining.Theissueatlhecoreoflhisworkislhepolentialforicebergkeel

ObjCCI impacts or interference from trawl gear. In icc environOlentsthegoalisiccbcrg avoidance or iceberg resistance. Forsubscafacililicsextcndingabovctheoceannooror

contaCI.Thcparamelersinvolvedinthecalculationorriskwith frec-noJlingand

The goal of this study is to assess thcpotential of protecting singlc salcllitc oil producing wcllsusingaslrucluralframe.Toestimategloballoadsimposedduring the ice keel-

encrgytoworkdonethrough crushingandpitchandheavemolions.Basedonthe analysis. a simplificalion of the energy modcl is used. It is assumed conservatively that energyisdissipaledincrushingfailurcoficeoverthccontactarca only

ThcloadsdctcmlincdfromthisapproacharclhenapplicdtolheprotCCIion frame using

dcvelopcdtosimulatepile-soilinteraction.soil-struclurcbearing interaction and global siruclurcrcsponse uponapplication ofmcan globalicccrushingprcssurcs.Thrce differcnl struclural configurations are analyzcd and thcresults arcdiscusscd indctail Finally.conclusionsofthepresenlsludyaredrawnandrccommcndations put forth for sarcguardrorsinglesubseasatellilewcll installalionsagainstice keel coniaci. Theintenl is not to propose this ideaasthebestsolulion,ralhcrtoverirywhelherornolproteclion

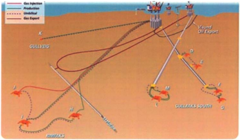
Thedcsircd resuh orthc analysis is a nearly optimal proicciionstruciure.Thefirsl stepis

space ror ROY access and workovcr. There shouldalsobcsurticientclearanee 10 allow

configuralion will bc made more nearlyoplimal lhrough successive ilcrations.The analysis will begin with a simple rectangular rramc. similar toconvcntionalprotcction

Iruncatedconcwilh straightinclined mcmbcrs. Thc1funcalcdconewillthentakc more oradomedshapcas lhecrrectivcnessorprolcction frarncgeomelry (i.c. curved vcrsus

Figure I depicts Europe's largest fixed-platroml subscatic·back dcvclopmcllt.the


Gas Injection
Production
Umbilical
Gas Export
K
GULLVEIG
Visund
Oil Export
D
E
M
F
L
GULLFAKS SOUTH
G
J
H
I
RIMFAKS

prodUClion lrcc. lypically called Christmas (Xmas) lrce.and wellhead. The Xmastrcc

comprises **valves,** spools and fillingswilh a primary function lodirccl and controlnuid

hasarclalivelylowprofile height versuslheverticaltrcc leading l0 a reduction in contact

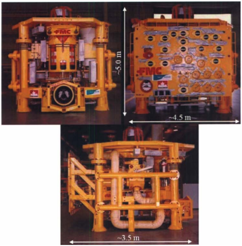
catastrophic failure modes. In the event of a dircc1 iccbcrg impacl with atrcc. prevention

production tubing. Strcsscs induced in the production tubing. criticaltorcliablcsafcty

valvcopcratioll.willlikc]y behigherforahorizontaltrccappiic:nion and rccomplcting

polcntially bcrcalizcdwilhthc implcmcntation ofsufricicnlimpactprolcclion

Figure2providesapproximalc dimcnsionsfor a typicalhorizontnl trce used offshore



protection structures. ThreeslruclUral configurations have bcen conceived based initially

analytical cxpressions lhal account for the syslcm energycomponcntsandicecrushing failure mech

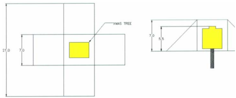
modeled usi

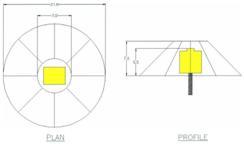
by piles con

discrete nonl

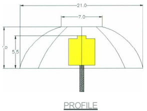
(2000) guide

The global structural responscofarectangulartubular·framestructure (Figure 3) will be compared 10 that ofa truncated cone slructurc(Figure 4) and then Ihe potential benefit of introducing curved members will bcexamined aSlheprotcctionstrucluretakes a dome-like shapc (Figure 5). The reclangular frame slructure. including pile foundalion. has an





Figurc4-Truncatcd Cone Prolection Structure



3 INDUSTRY OUTLOOK

As large offshore discoveries become

economic development of smaller fie

potcntial of lhe Wesl cxtension has received continucd interest (Husky Energy.2008) Expansion plans for bOlh thc Terra Nova and Hibcrnia ficlds also indicate the trend in harncssing lhe full polential of Tewfoundland and Labrador's oil and gasresourccs. The following figure shows lhe approximate locatioll of thcaforcmclllioned fields with

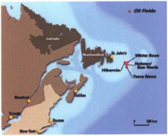


Figure 6- Offshore Newfoundland and LabradorOilfields(Rigzonc,2008)

As costs escalate due to strong global demand for scrviccs. resources andmalerials.itis bccoming increasinglydifficull 10 make project cconomics work. TheWhiteRose Southcrncxpansion. for examplc,addsonlya IO% incrcmcnttothestated oil reserves but will cost 25 % of thc original White Rosedevclopment budget (TheCanadianPress.

provi nce iscxpcctcd to reach the 400,000 Barrcls pcr Day (BPD) mark withproduction

expansion of the industry. largcr stand-alone fielddevclopmcntsor smaller field developmcllt withtie-backstoexistinginfrastrueture is required. Park (2007) discussed production trends for the threecurrent producing fields on the Grand Banks: in 2007.a30 pcrccnt decrcascin production was prcdictcd by 2011. Withoutadditionaldevclopmcnl

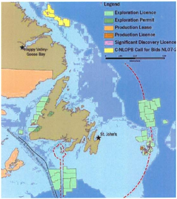
Themajorilyofoil and gas aClivity has bccn focused in IheJcannc D'ArcBasinwhichis onlyoneoffourbasinsonlheGrandBankswilhthcgcophysical characlcrislicsofoil-bearing rock. AlldiscoveriesonlheGrand Banks lodalc have bcen inlhisbasinwhilc

There arc approximatc ly4 million hcclares undcr liccnsc in thc offshorcarcasof

cxplorationliccnscsgranlcdforlesslhanaquartcr ofthclotalavai lablctcrrilory.Asa rcsultofthrccscparatcbidscallcd by theCNLOPBin 2006,six ncwcxplofationlicenses have bccn grantcd for six parcels comprising a tOlal of 604,647 heclarcs. Threcof these parcels, which make up approximalcly 13%ofthetOlal area, arc locatedin the Jeanne O'Arc Basin while the rcmaining area is in the Weslcrn Newfoundland and Labrador offshore region (Oepanmenl of Natural Resources. Gov. NL.2008). The number of

- 328 wells had been spudded (spudding is Ihe very start of drilling on a new well).
- IOlalinduslryexpendilurcswasapproximalc!yS2Ibillion(>l.8billion on

barrels of natural gas liquids had been discovered (Department of Natural


Legend
Exploration Licence
Exploration Permit
Production Lease
Production Licence
Significant Discovery Licence
C-NLOPB Call for Bids NL07-2
Happy Valley-
Goose Bay
St. John's

4 SUBSEA PROTECTION

4.1 Conventional Protection

4.1.1 Protection Frames for

thal lhere is a large enough risk of accidental loading. Ihen some means of protection mustbcprovidcdto protectagainsllheseloads. Protcctionframesapplywhen there is a risk of dropped object impact loads or snag loads (fishing gcar. anchors). Work is currently ongoingfortheassessmentofprolcction strocturcs towithsland stronger and

requircmcnts forovcr-trawlable and dropped objecl protection struClures. Maximum loadscxpeclCd from droppcd objcct impacls and fishing gcararestjpulatcd.Foralllulti-

is given as 50 kJ. A maximum load of 1 MN fr0lll traw[ground rope snag is given in the progressive collapse limit Slate (PLS) for a non-overtrawlablclnon-snag-frccstructure

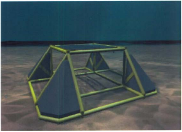


Figure8-GravitySubsea Protection (GSP) Framc (Arup Energy. 2(08)

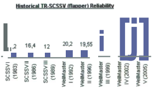
Fail-safe well features play a very important role when evaluming grcquircmentsfor wellhcadprotection.Currcntly.failsafesystemsareadoptedasapart of the design on every well drilled and pcrforman important safety function.espccially for offshorc installatiolls. Thcscsafctysystclllsarerequircdloprcvcntinjurytopcrsons.damagcto

Subscacomplctions,whichincludeintcgral wellheadcomponellts.should bedcsigned to

type of fail-safe systcms adoptcd for well installations is the subsurface safety **valve** emergency such as a wellhead failure. Thcsafely-valvc syslcmisdesigned 10 be fail-

Perhaps Ihe mosl regulated componem ofan oil and gas well. the SCSSY Illustsatisfy stringent technical. quality and operational requirements. IIIC induslry has madc huge

rcliability.Thcfigurcbclowil1ustratcsthedcvelopmcntinDappcrtypc downhole safcty



by lheFoundation rorScienlificand IndusIrialResearch allheorwegian Inslituteor Technology(SINTEF)and iscurrenllymanagedby Welhnaslcr. Thisstudyremains lhc largestyel undertakenintosubsurtacesarely-valveoperational cxperience

SarCIY valvesshould be installed at sufficient depth in thcproduction string 10 maintain inlcgrilyas lhcyorrcr a major risk or environmental dalllage ir compromised. Orrshore

in lhc tubing string at least30 m below theseanoor. as slipulatedby lheCNOPB under

An analysis perrormed by Doha (2007) provides insight inlo thesarc rangcordcpths at which certain downholecomponenls may bescl. Significant stresseswere round IObe nonexiSlentat typical SCSSY inSlallalion levels. RelianceonSCSSY's and other rail sarcsystemsorrersan obvioussolution ror reductionin ovcmllriskand up-rronl ponionoflhe Xmas Iree.can be placed under a safcly class 2dcsignationascenain

componcntsdonolcontribulcgrcatlytowellintcgrily.Thiswouldeffcclivelyreducclhc

unprolcctedwcllinslallalionwouldbereducedtoapproximatcly9.7xlO-j wilhoulice

managcmcnl.Thcsccstimatesprovidemolivationforfunhcrstudyofthcstruclum l

Foran unprolccted well. Fowlow (2007)cslimates an icebcrgcontaclprobabilityof9.6x

10^{-4}. By refining safely class designalionsoflheChriSlrnasIree.approximatclyl7%of

the lrcc area can bcneglected. achieving a C0lllacl probabilityreduction of 17 %. C-

given icebcrgconlacl hasoccurred. isapproximatclyO.097. Integrating this suggeslion

as well as an SCSSV probabilily of failurcofO.027 an overall blowout probabilityof9.7

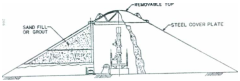
51.1 years. Fowlow (2007) uses a more conservative valucof36.7. which resulted from

for Olhcr polcnlial leak sources. In addition.thedalasct may not accounlforlheinlcnded resulting from icebcrgcontaci and the corrcsPOnding effect on SCSSV reliability and

To keep rescrvoir Ouids separate from Iheenvironmentlhercareasericsofbarriersina wellcomplction.Primarybarricrsareinfull-timedircclconlactwithhydrocarbons sccondary barriers exist as a backup in caseofa primary barrier failurc andlcniary

Doha (2007) pcrformed a fault tree analysis l0 roughly prcdici Iheovcrall probability of failurcofallwc]lintcgritycomponcnls. Failurc ofproduclionlubing and annulus

11lbinghungcrandlwoSCSSV·sbe]ow.Thcscvalveshavehighrcliabililies and Iheir combined cffons give a probability of failure ofapproximalcly 8 x 10.7. Tllcunnulus barricrs- packers.ca<ingjoinls. tubing hanger seals. and annularisolulionvalvcs-givea mlich grcalcrovcrall probabilityoffailurcofO.987. Thcresullingprobabilityof hydrocarbonrclcase lo1heenvironmcntisapproximalclyO.O I27. Thisfaulttrccanalysis waspcrformed giving thercliability ofallpolenliallcak sourccsequal weight. when in



TYPICAL WFltHfAQ PROTECTIVf ENCIQ$I!Rf CONCEPT

Figure I|- Proteclive ShellerConccpt (Pctroleum DirCClorate.Gov.NL.1 981)

DORIS Engineering perfonned a dctailed study in 1999 on altemativcs to glory holes

protect onc to thrcesubsca tcmplatcswhich rcquirc a much larger stnlcturcthanwould be requi red by a single satellilc well. Noncthcless.thecstimalcdiccbcrg loadingand ncccssaryslrtlcturcsidcslopewouldapply. 111c minimumheight waschosenas 1Om

scabed, A horizonlaltrce. usuall yaround5mhighwouldrcqllirc a structureabOll 8 m high, Figurel 2 iliustratesthetypicaiprolcction siructurcarrangcmcnLAnicecrushing strengthof2MPawas utilizedindetermining ice loadswhichranged from a rcsultanl of

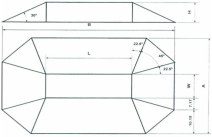


Figure 12- TypicaIProtcclionStruclure Arrangement (DorisEnginccring, 1999)

The fol lowing poinls briefly outline lhe various slructures considered

sloping face design and external shell of concrete or stcel. To be floaled and

wcightversionwasconsideredtoreducei nstallationweighLThisversionwould

separately constructed and transported elcmellts. Similar to the monolithic rigid

- Piled segmental rigid structure; this solution was shown lo requirca large number of piles lo resistthe latcralloadsand therefore was n0l investigatcdfurther expected leading 10 the requircmcnl foraconsidernbleamounlofaddi lional

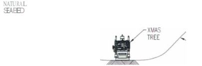
AnOlhcrapproachthalhasbccnc,Ilamincdisthcconslruclionofaprotcclivc bcrm around

practicalityofthisconccplisrcstrictcdbythecxtcnsivc:lmountofslrUcluralmatcrial

BOllomscouring icebcrgs havelraversedregionsofg]oryholcinstallations at depths of uplo I.5minlhepast(C1ark. Hclheringlon.Zavitz.&O'NeiI.1997). Thc level of unccnainly and prudence for eslablishingaconservalivedcsign basiswilhrespccl10 safely largcls has led reccm developmenls on lhcGrand Banks, namcly Whitc Rose and

Opcn glory holcsoriginatcdwhendrilling aclivity bcganin shallowwaterrcgions in lhe

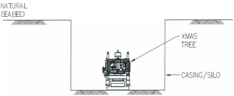
incorporated opcn glory holcs providing about 4 lll of scour protcclion (Carrick. Delong.



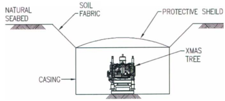
Difficult groundcondilionscrealcdtcchnical challcngcsforbolhlheTcrr30vaand WhilcRosegloryholeexcav3tions. Cost implications of large opcn glory holes provide reasolllocrC3lccheaperahemalives. Wilh ancstimalcdcosl ofS9.55 MM CDN (2007). gloryholcsarenotarcasonableicebergconlacldcfcnscsolutionforsinglcs31cllitc

typically6tolOmctcrsindiamcteranduplo20mdcpth.lnstallationwouldnorrnallybe carricdoUl fromadrillingrig.Thesilo isinstallcdpriortocomrncnccllcll1 ofdri llin g opcrations, Thcsilohasawcakpointatapre-dctermincdclcvationbelow sea level. In the case of iceberg impacl. the silo is sheared at the weak poillt andlhcuppcrpartofthe si lo is sacrificed. leaving the lowerpartofthc si lo,thc wellhcadandthcChrislmaslreein

A fieldlrial in 199010 assess the feasibi lilyofusingTornado Dri ll@**technologyshowed**



scgmcntbyslopcdexcavatedsidewalls.Soilreinforcemcntfabricmay bc applied to the sloped excavations if necessary to avoid soil slippage. Aninnerprotectiveshieldcould alsobc incorporalcd to protcct the produclion equipment from debris and makecleanup



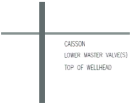
multi-well cluster tie-back developments from a risk and cost perspective. The modified cased holeconcept wasfoundtobcthe mostattractiveoptionfromacombincd cost and asscmblyconsisisofall componenisessentialformainiaining wcllintcgrily. Thc

damage during shear link aClivalion a breakaway flangc may bc incorporalcd abovc lhe

special running lools and consumablc caisson materials arc required (Fowlow. 2007)

Thiseonccplhas bccnimplementcdonfive explorationwellsollthcGrand Banks by

as productioll welts if the fields arc found 10 be eornmcrcially viablc ata lalcrdalc. As discusscdby Fowlow.CFER (1988)invcsligalcdthe collapsc bchavior ofthcse 1.067m caisson complclions 10 assess thc effectiveness ofthc intended proteclion system. While lhc relativcly unsophisticaled analysis yielded favorablc rcsults. unccrtainlies in caisson strength and soil parameters were sufficient to suggcsl thai in SOlllCSituationscaisson



Figurcl7-CaissonComplelionMcthod(Fowlow.2007)

pipcbcncaththcoccanfloor(Ocean Induslry, 1978). Thcabovc-mudlinc height was signilicantlyrcduccdlo 4'6'"(approximately l.5m). MaSlcr valves and other critical portions of the syslcm are sunk toa required dcplh and arc designed l0 au(omatically shut

notincludcany critical pressure-containingcomponenls andinthis parliclilar dcsign is covered by a protective dome. New design (caturcs (or this concept were prototypcd.

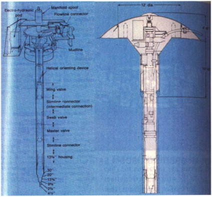
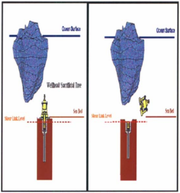


Figure 18 - Cameron Ironworks Caisson Completion System ("Ocean Industry. 1978)

The concept proposed by Doha (2007) uses off the shelf components and can be installed using standard procedures; a convenience feature which would increase attractiveness of any new concept. The difference between this concept and the caisson completion system is the non-requirement for a lower tree assembly. Instead, a single isolation ball valve is installed above the tubing hanger. Between the tubing hanger and weak link in the caisson completion system, there consists a lower and upper tree assembly compared



Ocean Surface
Wellhead/ Sacrificial Tree
Sea Bed
Shear Link Level
Ocean Surface
Sea Bed
Shear Link Level

tubing. The intention of the pipe-in-pipe cross scction is to decreasc stiffnessattheshear

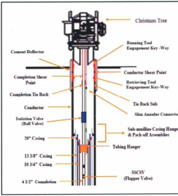


Figure 20 - Arrangcmcnt of Shear Link Wellhead System (Doha, 2(07)

ofthisconccpt is that no special tools. cxtra excavation or vcsscl requirement beyond a drilling rig arc required for installation of sub-mudlinc casingandtubing hangers. All

major factor in the relative economic attractiveness of this coneep1. Adownfall ofthis concept is thai while shear links arc inlcnded 10 rclieve horizontal loading.theywould not prevent damage from significant vertical forces. Thevertical forcescrcatcdduring

Ihcinleraclionprocessmaycompr¢SS lheshcar-link disconncctmcchanism inhibiling

opcrationofwellintegritycomponcnts. lnasamplccalculmion,Doha(2007) assumes

in estimating an ovcrall risk level of 1.27x 10^{-6}, which is less than lhc largctsafclylcvcl

of 1 x10^{-S}. If wcassumeice management isunsucccssfullhecstimalc is increased 10

A lhree year program by GERTH (Groupcmenl Européen de Rccherches Technologiqucs

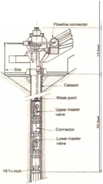
sur lcs Hydrocarbures) started in 1976 with the objcctive of dclining and studying a

design ofasix-momh.per-yearproduclion scheme as illustrated by Figurc2 1 (sec Duval

To place critical componcnlSoUI of range of scouring icc kccls il was decidedloplacelhe cquipmcnl on Ihc boltom ofa glory hole. Thc Xmas tree slood at a height of4 mwilha5

pUI in place 10 avoid filling by soil cave-ins. Tubinghangcrswerc locatcd in a1 m caissonapproximalcly 17mbclow lhccxcavation bonom.Thccaissoncornplclion syslcm consislcdof a lower lree assembly (slim conncctor and lowcrmaslcrvalvcblock) and uppcr trcc asscmbly (uppcr fail safe mUSlcr block. weak poi nt,cxtension,wye divcrtcr,wcll vcrtical accesssyslem, nowlinccconncction systcm). Thccrilicalprcssure-COlilainingcomponentsarclocaledbclow lhewcakpoinl. Tllcwcak point isincorporatcd in lhis particular design as a safety measure in the improbablccvent ofaniccbcrg kccl scouring deep enough toi mpaci thc subsea structure. Thetwohydraulicallyconlrollcd

Thisconccpl includcs three separate proteclion schemcs in onc: opcn gloryholc.cascd glory hole. and caisson complelion. ForapplicationonthcGrandBanksorinanyothcr design rorsarety has had years to develop since this study. The novellyor operalingin



Figurc2 l- Multi-ProtectionCol1cept(Duvalet al.,1980)

development in orrshore ice environments. An in depth risk analysis is conducted ror eachconceptaswellasadetailednelcostanalysis.Orseveralnovel concepts prcscnted. only the Xmas IrCC with downhole weak shcar plane and the modificdcased glory hole options were deemed worthy offunher slUdy due to their favorabilit y from commercial.

caisson complction systcm. Astrucluralbascdfinitcclcmcntanalysis was conducted to prcdictstructuralrcsponseofawellheadtoiccbcrgcontacl.Optimallevclsforkey componcnts of the complction are suggested. Rcsultsofariskanalysis based on contact frequency and available reliability data show the potcntial effecl.S of including downhole

Asdiscusscd by Doha (2007), it would n0l bceconomically fcasible for rcscrvoirslcss

protection. A recommendation for new subsca protcction ideas was putfonh

Fowlow(2007) pcrfonned an in-deplh risk and cost study forlhc various prolcction concepts. Single well devc[opment scenarios as wcll as multi-wellclusterarrangcmenls were analyzed. The annual contact probabilily wascalculalcd foreach conccplulilizing

effccts of iceberg management with an assumed 85 %cffectivencss. From a purely risk based pcrspective. assuming that icc keel contact results in a well blowout. it was suggested lhal opcn glory holes and modified cased glory holes arc lhe mostfavorable rcduccd by shortcning the spacing bctwcen Xmastrces in thcclustcr. Fowlow (2007) suggcstedchangingthe minimumwell spacing from 25mtoiO mtorcducccontact

Thecostofdevelopinganoilfieldisgenerallyhighcroffshorccwfoundlandthanin

cost analysis was undertaken for the aforcmcntioncd wellhead protectionconcepts. The net cost ofa particular system is evaluated using the following expression

whcreC\,y isthe net incrcmcntal systcmcost equalto the incrcmental CAPEX cost (C_{CAPEX}) plus lhe cost of risk from icebergs (C_{RISK}). Cost of risk can be cxpressed as

where, fl is theannualprobabilityoficebcrgcolltact. R is equipmcntrepair/rcplaccllcllt cost, Eiscnvironmcntal and equipmcnt clcanup cost. L_p is cost of loss produclion. and

singlcsatellite well development based on nct cost. Whilc an unprOlcclcd well with and threshold safely limit of 10^{-5}, based on the assumption that iceberg contact causes a well

comparison of the associated costs for each concept. CAPEX has the greatest influence

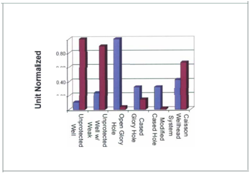
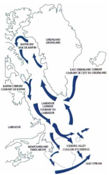


Figure 22 - Unit Normalized CAPEX & Cost of Risk (Fowlow, 2007)

Thc majorilyoficebergs that find lheir way l0 thc Grand Banks calveoffoflheWcst

Jccbcrgslravcl orthinlheWcslGreenlandCurrcnl.lhenSouthinthcBaffinand

2003). Figure23outlineslhcgcncraltrajcetoryoficebcrgslhatmaydriftinloregionsof



Icebcrgsrnaybcfreely-floatingorthey mayalsocolllcintocontactwiththeseabcd causing scours (gouges) or pirs. It is worth noting that theCanadian term 'scour' is synonymous withtheU,S, term·gougc'. The numbcroficebcrgswhichenter the Grand

iccbcrgseasonextends from March through June. While iccbcrgs arc great spectacles for

Acceptable safety or reliability targets associated with subsea installations in ice

orrshorccodcs providc the besi design guidance relating to Grand Banks icc issucs

		Target Annual
	Consequences of Failure	**Reliability Level**
Safety Class 1	Great risk to life or high potential for environmental pollution or damage	$1x10^{-5}$
Safety Class 2	Small risk to life and low potential for environmental pollution or damage	$1x10^{-3}$

installation is lhercfore $1x10^{-5}$. Up 10 aboul ten entities can be treatedindividuallyatthis

safcty lcvcl bcmaintainedatlxlO-l.therebyincreasingthesafctyrcquircmentforeach

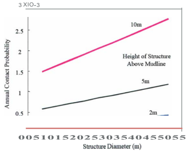
or injection wells. the environmental impact will bc lcss scvereand thercforcthcsafcty watcrlincstructurcsbeseparatc from Ihcgcneral sea icc load problem.lcebergloadsfor

They showed thccffect of lowering Ihe vertical profilehcighlofasubsca installation on

bctwcen 10^{-4} and 10·Jwhich is 100 high for a safely class I installation even Ihough a full well blowoul isnol necessarily a result ofimpaci. A main rccommcndalion from this papcr was to asscss Ihe risk loslruclurcs that prolrudc above the scaOoorbysimulationof

To assess icebcrgrisk l0 subsea installations which protrudcabovc Ihc mudline we need

l0iairiskoficeberglsubscasifUciureimpacl.Figurc24 shows theimportanceof



3 XIO-3
Annual Contact Probability
2.5
2
1.5
1
0.5
10m
Height of Structure
Above Mudline
5m
2m
005101520253035404550 55
Structure Diameter (m)

Table 2- Areal Density for Degree Squared Containing Major Developments on the Grand Banks

Time Period	Areal Density (Icebergs/Year/Degree Squared)	Source
1960-2000	0.60	Jordaan et al. (1999) in Fowlow (2007)
1981-2000	0.77	Jordaan et al. (1999) in Fowlow (2007)
1980-2006	0.79	C-CORE (2007)

In a report by Canatec Consultants Ltd. (1999), studies by Brooks (1985), El-Tahan and Davis (1985) and Miller and Hotzel (1985) were discussed. Brooks (1985) showed that an iceberg's waterline length is greater than its draft in about 92% of the cases analyzed

relationship was satisfied for 197 out of 214 icebergs (approximately 92%). Miller and Hotzel (1985) found iceberg width (maximum dimension measured perpendicular to long axis) was 85% of the iceberg length. From this result, a close correlation between

$$D = 1.03\exp(O.70+0.78\ \ln(L)+E_{,,})$$

whcrcell is anormallydistribulcdrandoOlvariablewithamcanofOandstandard

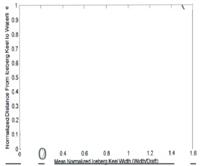
A recent report on ice management (AMEC Earth & Environmcnlal. R.F. McKenna&

Figure 26- PcrcenlugeofFrcc-Floating Keels Capable of Impacl (C-CORE.2007)

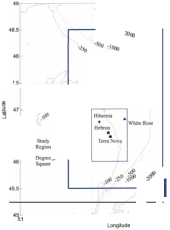
An expression relating normalized iccbergwidlh *(w^*)* to normalizedhcighlabovcthc

$$w^* = -9.31z^{*2} + 5.30z^* + 0.26$$

known profiles and recommendation is madc loincorpor::ucdata from manyicebergs:



Range	Mean Value
100 m > Draft > 90 m	0.22 m/s
105 m > Draft > 85 m	0.24 m/s
110 m > Draft > 80 m	0.30 m/s
Full Region	0.34 m/s
On-shelf	0.32 m/s
Off-shelf	0.35 m/s



Figurc28-DriftSpccdStudyRcgion(Stuckcy.2008)

Field specific cstimatcs of mean drift spccdshould consider the wutcrdcplhrangcofthc faciliticscornprisingthesubsea ficldlayoul. ltisconscrvalivclo usean cstimatc forthc clllirc study region in lhc above figure. The following paragraph is a review of other prcvious cSlimatcs of mean driftspced. however. lhercccnt workdone by Stuckey (2008)

IOO.OOOkm^2) includcSlhe ortheastGrandBanks.F1emishPassandthewestemportion

scourdcnsitywasO.56scourslkm^2 andindcpthsgrcalcrthanll 0m amcandclisilyor O.86scourslkm^2. ThevariabilityinlocallcvelSorscourdcnsityis notcd:thcrcare

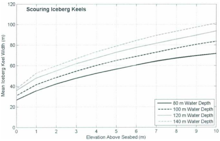
rcgionandameandensityofl.2-1.3 scourslkm!bctweenIOO-I50mwaterdepth (K.R

incorporated inlo the GBSC. A mean scour dcnsily or 2.64 scours/km^2 was de(ermined forlhe150km^2 rcgion

Geological Inference - Upper Bound **Geological Inference - Lower Bound**	8.3×10^{-5}	

Scour depths are difficult to measure consistently duc (oinformation from various

(Mycrs&Campbcll,1996)areinclose agreemcnt;forwaterdepthsranging from 80- 120



through an examplepcninent to this study. Thethcoryforthisapproach was first presentcd by Sandcrson (1988), whodevelopcd thc method todelcrminethcfrcquencyof

mclhods requiringcstimatcsoficebcrg nux. Thc followingformulac arc recently used where η_0 is the annual average areal density of icebergs, r_d' is the proportion of icebergs with drafts capable of contacting the facility, W_{fl} is the mean width of free-floating iceberg keels at the top of the facility, U is the mean iceberg drift speed, and O/ is

$$\eta_f = 0.032 \times \left(\frac{0.79 \deg^{-2}}{\cos(49) \times 1.237 \times 10^4} \right) \times 10^{-6} \; (46.67 + 21) \times 0.34 \times 3.16 \times 10^7 \; s/yr$$

$$= 2.26 \times 10^{-3} \; yr^{-1}$$

where p, is the scour rate, L is the mean scour length, W:k is the mean scouring iceberg keel width at the top of the structure, and O_1 is the effective structure diameter

$$\eta_s = 7 \times 10^{-4} km^{-2} yr^{-1} \times 10^{-6} km^2/m^2 \, (72m + 21m) \times 650m$$
$$= 4.23 \times 10^{-5}$$

$$\eta = \eta_f + \eta_s$$
$$= 2.26\times10^{-3} + 4.23\times10^{-5}$$
$$= 2.31\times10^{-3}$$

RClum pcriods for contact wilh each typc of approaching icebcrgcanbcdet**emlinedby** laking the inverse of the contact frequencies. Thcrclurnpcriodforcontaci wilh a freely-floatingiccberg is approximately 442 yearscomparcd with 23633 years fo**rascouring iccbcrg.llisclcarthatfreely-floaling;ccbergsdominalccontactrisklosubsea**

The addilional comacl risk from pining iccbcrgs (iccbcrgs lhal crcalC round or oval **fcalUfcson thcscabcd)willbenegligiblcwhencomparcdtolhcriskfmIII free-floating**

Tablc5- Inpul Paramelersfor TotalContacl ProbabilityofaSubsca **Facility**
Protruding Above lhc Mudlinc

	D_f		
Areal Density	η_0	0.79 /degree squared	
The Proportion of Icebergs with Drafts Between d_w and d_w-h	r'_d		
Effective Keel Width (freely-floating icebergs)	$\overline{W_{fk}}$		**SCClion5.2.4/Croasdaleelal** (2000)
Mean Iceberg Drift Speed	$\overline{U}$		
Annual Scour Rate	ρ_s		
Effective Keel Width (scouring icebergs)	$\overline{W_{sk}}$		
Mean Scour Length	$\overline{L_s}$		

in sccond place wilh 5 percent of operalions followed by water cannons. nclS.andlwo--

in somc carly reports. has been dismissed duc 10 the associalcd dangers (Barron ela!..

The following lablc gives lhc results of the analysis bascdon these twodcfinitions of low

Tablc6- lccManagemenI OperationalSucccss(Barronctal.. 2005)

Definition	Number of Operations	Percentage of Total
Operational Success	1492	99.1%
Technical Success	1287	85.5%

provides a good fit to empirical data for areas ranging 0.6 m^2 to 6 m^2. To delcnnine local

icc pressures (I_p) corresponding to an exceedancc probability (p_e) the following

$$I_p = \alpha\{-\ln(-\ln(1-p_e)) + \ln\mu\}$$

whcrc p canbedctennined with knowledgeofmcan evcntduration /and contact

Thctcnnpfcprcscnts lhenumber of eventspcrunillimc.Contaclfn-quency-which

(ramming of Kigoriak vessel. mean duration cquals 0.7 s). It is aSSUIIIed here that each

cOlltacl qualificsas an evcnt for further dctailsand cxplanation scc (Jordaanclul..1 993)

prcssufc-:ucurclationships forcalculation of global ice forces. Globalice crushing

pressure can bccstim:llcd by the pressure-area relationship

$$P = C_p A^{D_p}$$

whcrcC,,=Jand D,.=-0.4may betakenas mcan global values, dcpcndingonthe

applicillion. Jordaandiscusses how lhese resultswcrc dcrived rroma beslfitanalysis lo

ship ram data (Jordaan. 2(0 l). Both Cl' andD"can bc laken mndomly locxlcnd the rangeofrcalislic physical situations. The mean iS lakcn in thisstudy as a means of

Parameter	Mean	Standard Deviation	Distribution
C_p	3	1.5	Lognormal
D_p	-0.4	0.2	Normal

It isrecognizcdthathighlocal pressures mayexisl onsmallcrarcas.Local pressure

curve in Figure 30. Focusing on the 10.000 year local pressure curve il is evident that local prcssures at **areas** grcatcrthan around 13 m^2 acluallydipbclow pressuresexpected globally. At the point whcrc thesc curves inlcrsect u transition from local to global

mcan global prcssurccalculatedforlhe incrcmental area in contaCl.1f for cxamplcwe assumc full cnvclopment ofa single tubu!armcmber (with a normalprojcclcd area of approxim<ltcly7 m^2) uponinitial contactthcarca isalrcadyclosc to thc local to global

this preliminary analysis. Ihe effects of high local pressuresover small contactareaswill

procoourcs may bcst capture Ihis responsc mechanism and is a recommended courscof

Parameter		
$\bar{l}$	Salde	Preliminary estimate (P. Stuckey, personal communication, July 20, 2008)
η	2.31 x 10	Calculated in Section 5.4

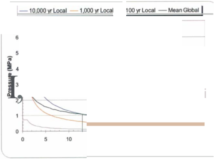


Figure 30- Local Pressure-Area Curves for Varying Return Period & Mean Global Pressure-Area Curve

Iceberg **keels** scour lhe scabed when Iheydrift inlo walcrdcpths shallow**erlhantheir**

playcdakcyrolcinthcmodeJ.whichbalanced sca**bedrcaclionforccs.cnvironmcnlal**

iccbcrghydrostalicsisascnsitivcparamctcrinrnodclingthc scourprocess.Limilcd

hydroslalicsand conscqucntly leads to significant differences in rnodclcd scQurlcngths and scouring icebergs were considered. Bascd onlhecontacl area,a forccwascalculalcd from the sampled pressure. ContaCI areas rcsulting from free-noaling and scouring icebcrgswcrcconsidercd in the analysis. Pressure wasassumed to develop uniformly over the entire rigid-bodycontacl area and all impaclS were assumedlobe dirccthils

with drafts capable of impacting a smellilc well 5.5 rnin height will pitch sllflicicntly to allow the keel to pass over the lOP Oflhe struclurc. Forlhe rcmaindcr of the icebcrg population, lhcdistance required lo dissipatc thc kincticcncrgyof lhe iceberg was calculalcd based on inilial iceberg drift velocily, iceberg mass and impact forceapplied al

cebe rg T ype	Force (MN) Mean	Momenl (MN·m) Std.	Mean	Sid.
Free-noalin	3.3	4.3	9.2	6.6
Scourin	11.9	8.2	18.7	10.3

excccding2.8 m^2 10eSlimaie ice keel forces on ahernalivcproteclion Slntcturcs for the

loads ranged from a rcsultanl40MN-200MNon struclureswhich varicd grcally in

iccbcrgs with subsea silos would be in the order of IO-30 MN with significantdownward

iccbcrgs.Thcsignificanldownwardsforcesmayhavebccnaresultofconservatismin estimating ice crushing pressures. The coerficient C,.is taken as 7andlhecxponcn1D,.

sacrificial well cquipment be localedabovclhcscabed and crilical cquipmcntbeinslalled

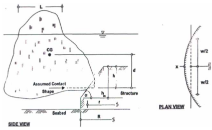


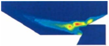
Figure 31-Gcometry of Truncated Cone (North Atlantic Offshore EnginecringAlliance.

As part of lhestudy, lhc delermination of iceberg loads by cncrgyconscrvationand mOlllcntumconservation approaches was invcsligated, Aswe1l.anumericalmodcl of iceberg mOl ion was accompli shed using the discreteelcmenl compuler package known as

A recent study by Gudmcstad and Liferov (2007) assessed icc loads of an ice-ridgekccl on arigid subseaslructure.Twosimplified2Dnumcricalmodclsweredcvclopedl0

cohesion, kccl angle of intemal friction). Thcanalysiswas pcrformcdfor shallow. intcnncdialCwatcrdCplhs in icc covered walcrs. Asamplcoutput graph showed annual cxcccdancc probabi lity versus comacl force pcr mClcr(width) for a lOmwidcslruclure cxtcnding5rnabovcthcmudlinein 30 m water dcpth. It wasdelcrmincdthatkccl deplh orcontaclhcight. hasgreatest sensiti vity. Possiblcintcractionscenarioswcredcveloped

Confined kccls, with lhe hi gh driving forces Oflhc surrounding icc noe were presumed 10 either shcar at lhc keel. or fai l locally and/or globally, Resultsof lhc analysis showed thai in all but two cases, local propagating fai lure was the mechanism that limilcd the kccl



The energy approach described herein follows the samc procedure outIinedinthc1996

rclationships had to bc modified accordingly: cxplanmion is given throughout this

Icc loads imparted on a subsea structure can bcestilllatcd using an applicalion ofthc work.energyprinciple.Uponimpact.thcinitialkineticcnergyof the iccbergwill bc dissipated through crushing of the icc keel (indentation energy),rotation and heave of the iccbcrg, and strain energy dissipated by the major load carrying componentsof the

Energy.2<XXJ). Theapplicalion of lheenergy approachinlhissludy does nOl account for

where $KE_{initial}$ is the initial kinetic energy of the iceberg, E_c is the energy absorbed in

sliding(or crushing). E. lhcenergy inlifling lhe ieebcrg.and El' inrol3ling lhe icebcrg

whcrc mis m3ss. c.. is anaddedmasscoefficicnland I' is lhc asSUlllcddrift spcedoflhc

walcr surrounding the iceberg. The added masscoefficienl can vary bctweenQ.OSfora cxtrelllcly highnorlllalforces arc gcncratcd on contacL Norlllalandfrictional forcescan

The moment generated due to lhe forces at Ihckeel can bccalcu]aled bymulliplyingeach

forcecomlXmentbyilSpcrpcndiculardislancctolhecenlcr of gravilyoftheiccbcrg

Fromlhccenterofgravityoflheicebcrg.e, and e_z arelhe horizonlal andvertical

bcequalcd 10 the righting moment todetenninelhcamountofinducedrolalion.Righling

stability. It istherefore important to integrate stabilitycalculations when considering the

$$M_{righting} = \overline{GM} \sin\theta \cdot \Delta$$

whereGMislhedistaneefromthecenlcrofgravitytothemctacentric height and Δ is

where ∇ is the submerged or displaced volume. The distance $\overline{GM}$ isgivenby where $\overline{KB}$ is thcdislance from lhe keel 10 cenler of buoyancy. $8M$ is lhc dislancc from thecentcrofbuoyancytothemetacenlricheighlandGKisthedislancefrom the keel 10

$$M_{righting} = \left(\overline{KB} + \overline{BM} - \overline{KG}\right)\sin\theta \cdot \Delta$$

where $I_{...}$ is the moment of inenia of the waterplane arca. and ∇ is the submerged or displaced volume. Equation 6-15can then be rcarranged as follows

$$\Rightarrow M_{ri\cdots\cdot} = \overline{BM}\sin\theta\cdot\Delta - \left(\overline{KG} - \overline{KB}\right)\sin\theta\cdot\Delta$$

$$\Rightarrow M_{righting} = \frac{\cdot_{wp}}{\nabla}\sin\theta\cdot\Delta - BG\sin\theta\cdot\Delta$$

$$\Rightarrow M_{righting} = \left(\frac{I_{wp}}{\nabla}\Delta - \overline{BG}\Delta\right)\sin\theta$$

$$\Rightarrow M_{righting} = \left(I_{wp}\rho_w g - \overline{BG}\Delta\right)\sin\theta$$

Ifwc assumc lhatfor smallangles. sinB := B.thc cxpression canbefurlher simplificd

an icebcrgsome angle wilhoutperfonningdetailed slabilitycalculations. Foraninitial calculate the necessary applied moment at the keel to rotate the ice

estimate of the waterplane moment of inertia. Energy dissipated th

calculated by:

shapcdiccbcrg willbccxamined, Thekey parametcrsfrom a hydrostatic analysis will be

rOlatc uponinitial conlact. lesseningtheamount of energy tobcdissipalcd lhrough crushingoflhekecl.Encrgystoredinheavedisplacemcntwillin turnadd energy to the system in the form of polentiaI energy: the net balance will likely benegligibletowards lhedissipationofcnergy.Thefollowingpamgmphsprovidctheprocedurcfor

Assuming basc **keel** widlh.sidc+slopcangle(a)and height (h) allowsforcalculation of the radius of the top area of the lruncatedcone (refer to Figurc 33), Withthegcometry cstablishcd.hydrostaticscan be used lorcso]vckcyparamctersrcquircdtodetcrminethc stabilityofthcassumcdiccberg shape. Toobtainthcdcsirceddraft. the height can **be** adjustcdand lhe hydrostatics performed iteratively: thc foliowing dcscribes lhis process

After sclcclingabasc radius.side-slopcanglcandhcight.lhc topradiuscanbc calculated by simple trigonornetry.Thevolumeoflltruncatcd cone(inthisCllsc, thcvolullleofice)

where h, r_b and r_t are illuslrated in Figure 33. The weight of the icc (W_{ice}) which is equal tOlhe buoyant force (FB).can then becalculalcd by multiplyingthevolumeofice by the unil wcight. assuming the densily of icc is approximately 92**5 kg/m^3**

densilyofseawaterisl025kglm^3

$$V_{water\_displaced} = \frac{W_{ice}}{\rho_w g} \quad \text{(Eq.6-25)}$$

required; a solution can be achieved iterativelyorusinga solve **rloolsuchasgoalseckin** excel. Furthermore.changes lo lhegeometry(i.e.overallheighl)can be made to achieve the desired **draft** importantindcxofslubilityatsmallanglesofrolation.Sincewcaredealingwilh

symmctric gcometry in this example. there is no need todislinguishbclwccn longitudinal

can bccalculatcd by equalion 6-14. The location of the cCnlcrof gravityforatruncated

$$G = h - \left[\frac{h\left(r_t^2 + 2r_t r_b + 3r_b^2\right)}{4\left(r_t^2 + r_t r_b + r_b^2\right)} \right]$$

calculatcdusingcquation6-16,where/$_{Mp}$ foracircularwalcrplanccross sectional area is

AflCrcalculating these key parameters. it is relatively simple l0 ca!cu]alc the slability

curve ($\overline{GZ}$ curve) fOf the given shape. taking advantage of the small angle

approximation. With surticienlaccuracyforallpracticalpurposcs thedistanceGZcan foragivenangleofrolation.Knowingtheseparamctersrclaledloiccbergslabi lily

goometryduclorolationoftheicebergarenol accounled for. The normalcontaclareais

pressure can be approximated by the nominal pressure-area relationship giving normal

wi ll be a sharp increase. and lhe accumu lation of area will continue on linearlylhcreafler

angle of the strUClure and the coefficient offri clion belween lhe kecland slruclurcface

Figurc 34 illustrates the growth of the contact area wi lh hori zonlal pcnctrationaswellas

lhc normal and component forccs. Theappticdmorncntatthe keeli s then calculated

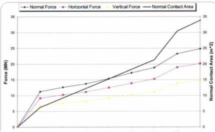
cnabling rcso lutionoflhe rotalionangle. We can alsoso lvc for lhe vertical uplift as the

displacemelllS. the work done by surge. heave and pitch motionscan bedelcrmined by

intcgralion.Thecumulativesumofenergicsaftcr eachincrelllentiscompared to lhe sample calculation is performed for a truncated cone shaped

rectangular frame structure as summarized by the parameters

Table 10- Sample Calculation Parameters Trunca



Normal Force
Horizontal Force
Vertical Force
Normal Contact Area
Force (MN)
Normal Contact Area (m^2)
0
5
10
15
20
25
30
35

of energies from each contributing mechanism with incremental penetration until all of the energy has been dissipated as indicated by the % Total Work Done line. From this figure we can see that crushing energy increases rapidly at first due to the fact that the

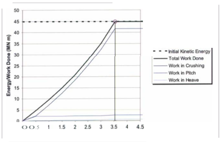
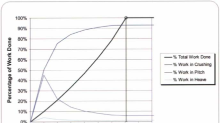


Figure 35- Work Done versus Penetration - Truncated Cone Iceberg Geometry



Figurc 36- % Work Donc versus Penelralion-TruncatcdConc IccbcrgGeometry

Tocslablish an uppcroo undeslimate ofinitial stability. andconversely a lower bound cSlimalCoflhe energy dissipaled through rotation. we can simulalc a rectangular prism shapc.Thisprcsumptionisbased onlhcidca thatlhcbalanccofmOlllcnlsaboutthc CClltcr of gravity will bc zero as the horizontal and vertical forccsapplied al the keel and the moment arms will bc practically the same. Thc calculationprocedure is the same as forthc previousexarnple, aside from thedifferencc in geolllctry. Thcfollowingtublc

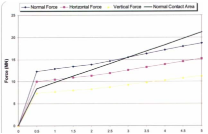


Figure37.ContactArea&ForccversusPcnctr.i1ion-TabularlccbergGeomelry

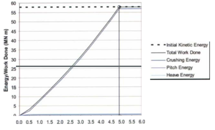
As can bescen in Figure 39. nearly all ofthc work is done by crushing of thekeel.The

stabilily in cornparison to the previous shape. Thcothcrfactorwhich contribulcsgrearly

ccnterlinc ofthc iccberg. Theappliedmorncntatthc kcclabollllhc ccntcr of rotalion is

equal lO the horizontal force at the keel multiplied by the distance from thc point of

horizontal distunce is only a small amount less lhan the vertical diSlance.thereroretheapplied moment at the keel is much lower than for the previous case. Frollthe results prescnted in thc following two figures. it is clear that the majorilyofenergyisdissipatcd through crushing bcfore the iceberg comes lO rest after surging almost 5111



Figurc3S-WorkDoneversusPcnclralionforTabularlccbergGcomclry

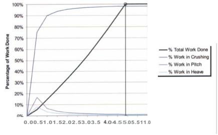


Figure 39- % Work Done versus Penetration - Tabular JccbcrgGcomctry

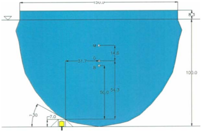
Theparallelaxislheoremforcompositesectionsisusedlofind G and B. Anelliptical

The submerged volumcand watcrplanemoment ofincrtiaarecalculalcd todclerminclhe

than the proportion from pitching. Thisislikclyduclolhcdifferencc in the slope of the

Ihcorclicnllycamc toreSI it had pilchcd abouijusl greatcr than 0.23° which closely agrees

with a mcan pilch of 0.24° presenlcd in a similar modcl used to prcdicl iceberg dynamic



	n/s

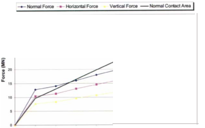


Figure41-Conlacl Area & Force versus Penetration - Mean Iceberg Geol1clry

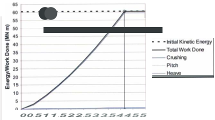


Figure42- WorkDoneversus PenClration- Mean IcebcrgGeomclry

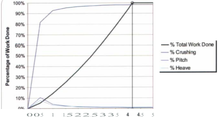
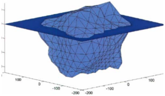


Figure43 - % Work Done versus Penelration - Mean IccbcrgGeometry

dissip31edcntircly through crushingofIhckcclmay be conscrvati vc in cases whcrc thc initial point of cont3ct is far from the ccntcr of rotalion ofthc iceberg. Thc rccolllmended course of acti on is toscalecxisting icchcrg profiles of icebergs suchIhatIhey wil l havc sufficicnldraftto impacta subsca slructureofa given height inu givenwulcrdcplh. For cachiccbcrg. Ihcstability uboutthcvarying dircctionsshouldbc dclcrmincd Rcprcscntati vc contact geometrycan be assumcd to producca contactarca-pcnctration

The iccbcrgin Figure 44 for example wi ll behavc differclltly based on the poinl of contacl. Thcmctacentric height will changeabout differcnt uxesaswell as the distance produce very different results with change in theoricntation of impacl. Application of

the Monte Carlo approach is recommended l0 cover a wide range oficcberg profiles Wilh



arc madclosimplifythe load transfer proccss. Sccnarios arcclcvclopcdto assess lhc

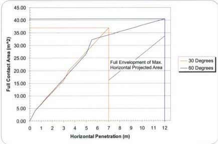
structural responsc of aprolcction frame to loads representative Oflhosc lhal woutdbe

imposcdduringcontactwilhanice keel. Although awidc fllIgeof iccberg load evcllIS

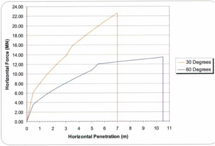
lhe icc-structurc inleractionproccss for conlaclwilh scabedinstallations. Based onthis

assumption. horizontal forces generated by ice crushing pressures and surgepenetralion

will be used conservatively tocalculale lotal workdone. Since hcaveandpitchmolions



Full Contact Area (m^2)
Horizontal Penetration (m)
Full Envelopment of Max. Horizontal Projected Area
30 Degrees
60 Degrees



Horizontal Force (MN)
Horizontal Penetration (m)
30 Degrees
60 Degrees

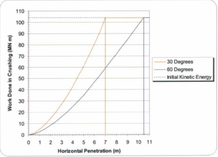
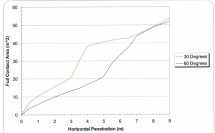
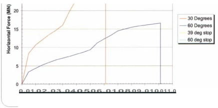
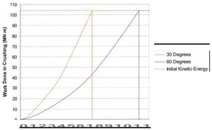


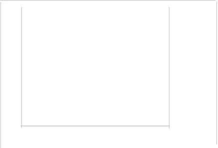
Figure 47- Work Done in Crushing versus Penetration (Rectangular Frame Structure)

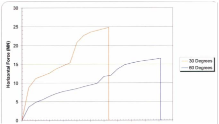
6.4.2 Contact with Truncated Cone Protection Structure




Horizontal Force (MN)
20
15
10
5
0
30 Degrees
60 Degrees
39 deg stop
60 deg stop


Work Done in Crushing (MN m)
110
100
90
80
70
60
50
40
30
20
10
0
30 Degrees
60 Degrees
Initial Kinetic Energy




30
25
20
15
10
5
0
Horizontal Force (MN)
30 Degrees
60 Degrees

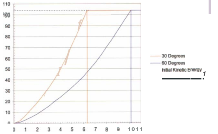


Figure 53 - Work Done in Crushing versus Penetration (Truncated Dome Structure)

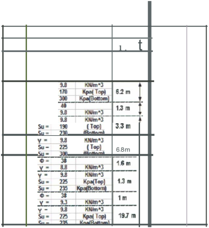
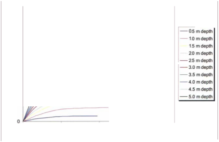
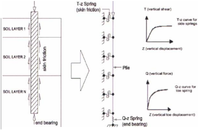


Figure 54-Soil Stfcngth Profile NW Anchor Pile White Rose Fielcl (Doha. 2007)

Each pi leconnccled to the structure is modclcd as a separate en tity based on the assumplion that si ngle-pi le load and dcncction charactcrislicswi llnotbcaffcclcdby adjaccOlpilcs.Generally,forpilcspacinggrcalcf thancightdiamclcrs. pile groupeffecis may not have l0 beevaluutcd(A.P. I.. 2000). Empirical methods. based on model and



0
0.5 m depth
1.0 m depth
1.5 m depth
2.0 m depth
2.5 m depth
3.0 m depth
3.5 m depth
4.0 m depth
4.5 m depth
5.0 m depth



where N_q and Nr arcbcaringcapacityfaclorsfor vertical slripfootings. loadcd verticallyinthedownward dircclion. Y istheeffectivesoilunitweighL risthctola]soil

$$q_{,.p}=cN_{,.}D$$

a relative displacement of approximately $\Delta_{qd} = 0.1D$ for granular soils and $\Delta_{qd} = 0.2D$

$$N_c = [\cot(\phi + 0.001)]\left\{\exp[\pi \tan(\phi + 0.001)]\tan^2\left(45 + \frac{\phi + 0.001}{2}\right) - 1\right\}$$

$$N_q = \exp(\pi \tan\phi)\tan^2\left(45 + \frac{\phi}{2}\right)$$

$$N_\gamma = e^{(0.18\phi - 2.5)}$$

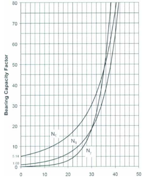
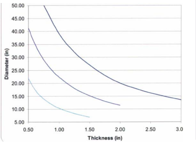


Figure 57- Plotted Values of Vertical Bearing Capacity Factors (American Lifelines Alliance, 2001)

distance 6qJ and remains constant thereafter. In the present study it is assumed that the

$$M_{applied\_max} = Max\left\{ \frac{w}{12} \left(6Lx - L^2 - 6x^2 \right) \right\}$$

$$M_P = \left(1.05 - 0.0015 \frac{D}{t}\right) \cdot SMYS \cdot D^2 \cdot t$$



Load.displacemenlrclalionshipsforlubularmembersofoffshorcstruclures impacted by

tool fora subsea lubular-frame proleclion struclurethcsamcfonnulaecanbeapplied.By

applyi ng forces resulting from pressures rcpresenlalive of icc crushing slrcnglh. we can

approximalclydclennine requiredmembersizestoprcvenlcxcessiveplaslicindenlalion

where F is the force and δ_E represcnts thcclaSlic displaccmclll,Eis Young's Modulus, '/

length of the conlact area along the direction of lhetubc. Thecharaclcristic length isa

discussed by Bai (2003). an empirical cquation wasobtuincdlhrough lhc analysis of

linear finilc shcll clement analysis results and indentation tcslS. A mean value is found l0

$$F_0 = 2\sigma_y T^2 L_C / D$$

indcnlation δ_p can be calculated using a semi-empirical equation. Through energy

unloadin g poinl.Thclocaldisplacemenlallhcloadpo illlforaloadlargcrlhanPoi s

As a s3mplc calculalion. scicCl u tubular member with a diameter of O.9m. and thick ness

Applying an effective area of

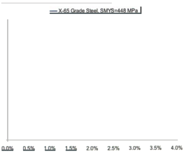
relationship gives $P = 3\times1.54$

gives a force, $F = 2.34MPa\times1$

clasticandplasticdisplacernentsareo "„ l8.36mmando/,=24.62mm.ASSllminga predictSlhe hardening behavior in theplaslic region of lhe Slrcss-slrain curve (Wikipedia

gradcs(Walkcr&\Villiams. 1995). Figure 59 shows a sample slrcss·Slfain curve for x-

		2.55	12.03
		2.23	13.67
(·52			17.99
(·56		1.66	
(·60		1.48	18.99
(·65			25.58
⟨-70		1. 13	**27. 13**
		0.86	37.00



modeledusingthcsameelementsasforpilcs(B31). Pipescclionsarc defined for the pileandslruclural member response is based on Timoshcnko beam lhcoryassuming

dcftncd by nonlinear spring elcmenls in two lransverse dirctions and the longilUdinal

oninpulparamclcrs(struclUrcdimensions.lubularmcmbcrsizc.pilcdcplh and sizc. and

prolcclionstructureis lhcncrcatedandtiedtolhepilcfoundation, The load application is

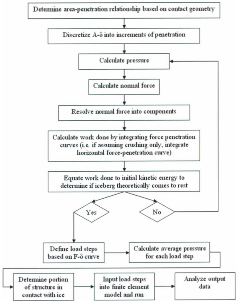
approachpreviouslydescribcd.Thc loadslcpsareenlcrcd inloan aulomalcd input file

gencrator which creates theinpul filc 10 bccvaluatcd by ABAQUS/Slandardwith

and vcrificationlhroughsimplestruclumlmodcls.h isrccognizcd lhat strcss intcnsity

analysisandcalibralionofthcftnitcelementmodclisrecolllmendcd

The following Oowchan oUllines Iheoverall analysis procedure. Themuin idea is that



Thissccl ion presents the resultsoflhe finileelement analyses descri bed in the preceding chapler. Thcre.'wltsare firSlillustrated for thc rectangular frame modcl.Theeffect of incorpor•uingcurved versusslraight members is then shown through comparison ofthe structural response of the truncated cone and dome models. Based on the outcome of

Note lhat lhe figurcs provided are scaled to improve visibility of the deformaliontrends:

undeformcd gcomelriesare provided in Scction 5.Conlacl arcasarc highlighled and

Table14-InputPararnetersforRectangularFrameGlobalStructural Response Analyses

cified)

Soil Type	Sand
ϕ	40°
$\bar{\gamma}$	$8.3 kN/m^3$

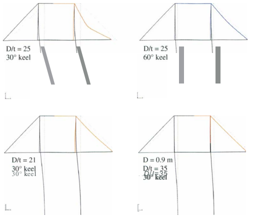


Figure60- GlobalStructuralResponseofRectangularFrameProtection Structure (2.5x magnification)

Pile Thickness	0.050 m
Tubular Diameter	0.6 m (unless otherwise specified)
Soil Type	Sand
ϕ	40°
$\bar{\gamma}$	8.3 kN/m^3

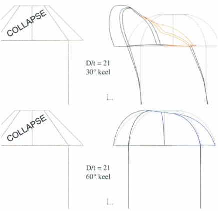
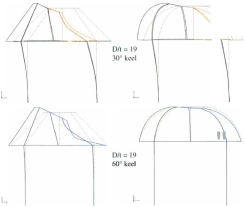


Figure 6.1-Comparison of Truncated Cone and Dome Structures (2.5x)


D/t = 19
30° keel
D/t = 19
60° keel

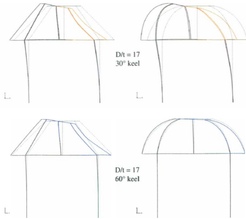


Figure 63-Comparison of Truncated Cone and Dome Structures(2.5x)- Continued

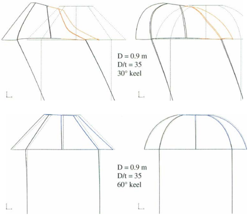


Figure 64-Comparison of Truncated Cone and Dome StruclUrcs (2.5x)-**Continued**

configuralions providing increased vertical support for lhe circular base models could

requiremenlforlhelruncalcdconcanddomcgcomctries.Thercclangular configuration

lhecircularbasc.adjaccntlomembcrsundcrdirectpressurc.forthcothcrshapcs.Since

thc sidc ofimpacl have displaced inwards about 0.9 m. The interaction with the 30" keel greatcr vcrtical componemresulting in less horizonlal displacemcnt than ilscountcrpan

Focusing on the frame response with D/I= 25in Figure 60. the point of firsl yieldoflhe

Figure 65. The area bctween lwoconseculivevcrtical lines reprcsents a load slcp. At

lhispoint lhcice **keel** has surged about 3 melcrs and about 27 **% of the assume**dinilial

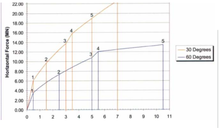


Figure 65- HorizomalForce-Penetralion Curvc - Load Slcp Scgmcnls

In a side-by-sidccomparison ofthe lruncatcd conc anddolllc modcls ihe results shown in

Figure6 1-Figure64consislcnl lydemonslrale lhe improvcdeffcclivcnessoflhe dome-

likcstructurein conlrolling high vcrtical loads imposcdbythc600 kcel. Comparison of

Figure 64. The added stirrnesssendslherorceslhrough lhe path or least rcsistance to the

To improve the perronnanceorthe truncated cone or domc modcls ilis recommcndcdto

thcywould likclybcmorecompetcntinlhccascororr-ccntcricckcclcontact

rcctungul ur rrallc configuration increases its attractivencss. Theinclincdsections

cXlcndingrrom each side orthc intcrior rrame could potentially bcconstructcdand create unique and eXlrcmechallcnges in every aspeCI of new developments largeand

A polCntial solUlion for lhe prolcction of single satellite wells was presented. Thrcc separate configurations were considered under the category of a tubular frame proteclion

Theencrgyapproachwasemployedwilh considermion ofi cebcrgstability for simple shapes 10 asscss global loading. Theinilialkincticenergyofsampic icebergs was cqualcd 10 thc work done in crushing failure of the icc keel over the contact area. and the simplification of the energy approach which conscrvalively assumed crushing failure

exc!usively - inlicu ofbettcrunderslanding-wasusedtopredicliceloads which were

predicled for each slructural configuration and a discussion of thc resullsensued

Thereclangularframeconfiguralionbehavedwellunderlhepredicted global loads. The

highvenicalpressureswithoutincreasing the member size relmive 10 the rectangular

frame model: venical sliffeningwasrecommended. In comparingthe lruncaledcone and bcrequircdlhallhearea-penelrationrelalionshipbcafunclionoflhckeel shapeofcach discrclcly simulated profi le. Dircct.cenlralinteraclioncvcnlswilhiccbergsltavcling horizontally have bccn assumed in the currcnt study. It is recollllllcnded 10 extend loading scenarios to incorporale non-central coniaci which would induce rotation about lhevcrticalaxis.Thepotentialforverticalimpactfroman iccbcrgwilh signific3nl heave

A potential avenuc l0 caplure varying stability and kecl geomctry is locmploy dislributionsoficcbcrg melaccntricheight (withassociatcdmass and vclocity tcrms)and keel angle. Withkcclangle.thearea-pcnctrationrclationship canbccstirnatcdbascdon cOlltactwithknowll Slructurcgeolllctry.Frolllthearea-pcnctralion curvc. thc crushing pressurccan bccaJculatcdfrolll which the normal forcecan bec:IJculated and rcsolvcd accordi ngly. Theapplicd horizontal and vcrtical forccsatthekccl detcrllline how much the iccbcrg wi ll pitch and heave depending on the stability of the icebcrg. which is represenled by its metacentricheighL Arnorcaccuraledcscription of the load path during lhc ice-structurc intcraction can bcachieved by updating the positionoflhckeel withrcspcctlothcstrucluraftereach incrcmcnl of hori zonlalpcnctration take advantage of the Coupled Lagrangian Eulerianapproachedbeingdcvclopcdin ABAQUS. although the conSlilulive models for ice would be a significantchallcngc

Further work on defining keel geometry is rccommcnded toasscss the gcncralpolcnl ial forkcel prolrusions l0 induce local member failurc. In addilion 101his. lhe effects of loca l icepresssurcson lubularmembersshould be asscsscd to furtherunders land potential

Sincc pile installationontheGrand-Banks maybcdifficult.itmayprovebeneficialto consider an alternative means toeslablish adequalc latcral resiSlance. Thcmaindownfal l

vessel support) and logislicsoplimization is needed. Oncc the slruCluralframe

"Oce:m Induslry.".(1978. *ovember).Belowmlld-Unell·ellcompleliollsystemlessells iceberg.anc!lor.lrawldamage.Oceall/lldllstry.13(1 I)64·65*

[redacted]

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pile thickness was not specified in the available literature. so a D/t ratio of 25 was

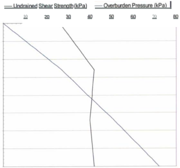


Figure 66-Assumed Undrained Shear Strength Profile (Karlsrud et al.. 1993)

is approximately 25 %. A comparison or bending momcntresponse rora20k ' loadalso

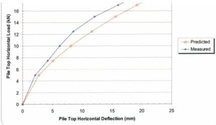


Figure67- Horizontal Load vcrsusLatcral DisplacelllcntinCiay

-4 -2 0 2 4 6 8 10 12 14 16 18 20

Figure 68 - Depth versus Bending Moment Single Pile in Clay

In a study which examined science and empiricism in foundation design, analytical

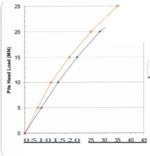
2003). As discussed by Randolph, the method of Jardine and Chow, known as the MTD

diameter pile of 50mm wall thickness. The pile embedment depth was taken as 100m.

in clay soil with properties similar to those found offshore West Africa. The effective unit weight was taken as 3.5 kN/mJand undrained shear strength (k **Pa) is approximated**

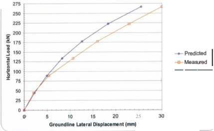
Figure69-Undraincd Shear Strength and Shaft Friction versus Dc**pthinCiay**

displacemenl oblained from the MTD mcthod and the API guidelines a**recomparedin**

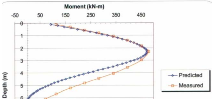


embedded to a depth of approximately 22m in sand with an internal angle of friction of 39° and an effective unit weight of 10.4kN/m^3. The water table was maintained above the ground surface during loading to simulate conditions which would exist at an offshore

pile, beginning with a load of small magnitude. Groundline displacements and bending pararnetcrsofthc field test wercrnatchcd in the numerical analysi s.Rcsultsshowedgood agrccrncnt betwccn measured and predicted groundlinedcncctions(scc Figure 7 I) with an average error of approximately 16.5 %. Abcndingmomemcurvcwasgiveninthe report for a 266 kN lateral load. Figure 72 displays a cOlllparison of the calculatedand measuredbendinglllomentcurveforthe266kNload.Excellcntagreclllcntisachieved

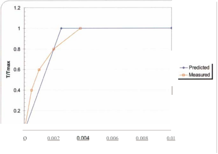


Figurc71- HorizomalLoadversusL.llcralDisplaccmcntinSand



A 1994 sludy by Al-Shafei el al. involved testing and analysis of tension and compression loads on 0.61 m diameter steel piles driven to 18 m depth in dense sand and

Figure 73 shows a comparison between the idealized bilinear t-z curve approximated using the API guidelines and the measured t-z curve from the physical test at 2 m depth



1.2
1
0.8
0.6
0.4
0.2
T/Tmax
Predicted
Measured
0
0.002
0.004
0.006
0.008
0.01